ESL-TR-91-29
Volume II

SEPARATION OF DEPLETED URANIUM FRAGMENTS FROM GUN TEST CATCHMENT, VOL II: CATCHMENT SYSTEM AND SEPARATIONS METHODS

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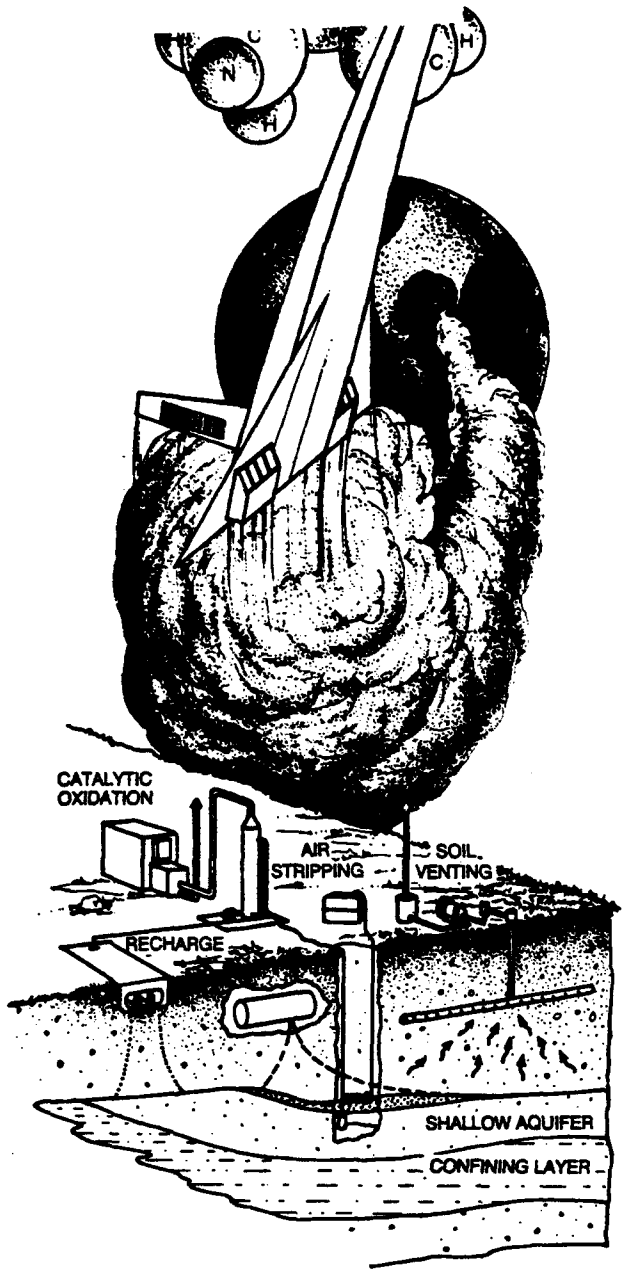
DECEMBER 1993

FINAL REPORT

SEPTEMBER 1988 - DECEMBER 1992



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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 30, 1993	Final

4. TITLE AND SUBTITLE
Separation of Depleted Uranium Fragments From Gun Test Catchment, Vol II: Phase I Catchment System and Separations Methods, Volume II of IV

5. FUNDING NUMBERS
C-DE-AC05-840R21400

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
ORNL/TM-11141

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)
HQ AFCESA
Tyndall AFB, FL 32403

10. SPONSORING MONITORING AGENCY REPORT NUMBER
ESL-TR-91-29

11. SUPPLEMENTARY NOTES
Prepared for the United States Air Force through the U. S. Department of Energy

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This technical report if divided into four volumes. Volume I presents Summary and Recommendations, Volume II contains Catchment System Evaluation and Separation Methods, Volume III contains an Economic Comparison of Disposal Options, and Volume IV documents Bench-Scale Tests for Separation.

Phase I activities are described for "Separation of Depleted Uranium Fragments from Gun Test Catchments, Vol. II," sponsored by the Air Force Engineering Services Center, Tyndall Air Force Base, Florida. The purpose of the work is the development of improved means for separating DU projectile fragments from target materials, principally sand. Phase I activities included (1) literature review of separations technology, (2) site visits, (3) analysis and description of current operations, (4) sampling and analysis of target sand material, and (5) evaluation of alternatives to sand as the bullet-stopping medium. Alternatives to the current separation and disposal procedures are identified which would result in significant cost savings over the life of the test facility. The most significant factor is an improved screening procedure that increases the usable sand life and decreases disposal costs. No suitable alternatives to sand as the bullet-stopping medium were found.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Separation of Depleted Uranium (U) Sand Depleted Uranium Separation (U) Gun Test Catchment (U)	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18
298-102

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PREFACE

This report was prepared by Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, DE-AC05-840R21400, for the U.S. Department of Energy (DOE) and the Air Force Civil Engineering Support Agency (AFCESA), Suite 2, 139 Barnes Drive, Tyndall Air Force Base, Florida 32403-5319.

This report presents the results of a series of activities designed to develop an improved method for separating depleted uranium from target materials, principally sand. Recommendations are offered for the most attractive method from both economic and technical perspectives. The search for an improved method considered the environmental, economic, and technical aspects of the problem. The method of choice is to dry, screen, and recycle the intermediate-sized uranium-contaminated sand. This will save the Air Force an estimated several million dollars over the next 20 years and will reduce the volume of low-level waste by about 90 percent.

This technical report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication,

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of the work described in this series of reports was to develop and demonstrate an improved means for separating depleted uranium from target sand, the source of the uranium being penetrator projectiles fired into a target building containing sand as the stopping medium. The principle incentive is to reduce the disposal costs of the contaminated sand by providing improved separation methods which diminish the waste volume.

B. BACKGROUND

The engineering and operational test firing of the GAU8 30-mm cannon produces low-level radioactive waste when the depleted uranium projectiles impact the sand contained in the target building. Test hazards and damage to the target building are held to an acceptably low level by periodically removing the large bullets from the sand. Proper operation of the filtration system on the target building roof during firing tests requires periodic elimination of the fine dust generated when bullets impact the sand. A third restriction on the amount of uranium contained in the target building is imposed by the NRC license which limits the amount of depleted uranium on site to *80,000 kg* but this limitation has not been the controlling factor in any of the test operations to date.

The present sand removal and treatment operations are of two types. The first is to remove the sand with a front-end loader and sift it through 1/2 inch opening sieve to remove the projectile fragments. The sand is then returned to the target building. With the second method all of the sand is removed from the building and stored on site in drums pending further treatment prior to shipment for long term storage at an off-site location. The target building is then filled with fresh sand.

These methods are effective but, because of the large volumes sent to storage, very expensive.

C. SCOPE

This volume reports on the following as specified in the work order:

Task I. <u>Literature Review</u>, including an evaluation of the current operation, evaluation of alternative means for separation of DU from sand, a review of uranium mining technology for

possible applicability to the gun test site, a review of previous studies in this general area sponsored by the Air Force, and an evaluation of alternative operating procedures.

Task II. Site Visits

Task III. Analysis of the Present Method

Task IV. Sampling Analysis, including the development of a sampling plan for the butt and analysis for the distribution of DU according to particle size.

Task V. Alternative Catchment Media, which evaluates stopping-media alternatives to sand and presents recommendations for future development.

Task VI. Summary Report

D. METHODOLOGY

The sand in the target butt was sampled according to a plan devised to produce a small quantity of material representative of the average composition of the entire target butt. The material thus obtained was subjected to a number of bench-scale tests of several promising methods of separating uranium from sand. These included two dry and six wet mechanical separation procedures commonly used in the mining industry. In addition two magnetic separation techniques, high gradient and open gradient, were also tested to determine their usefulness for the intended purpose.

Several computer runs were made with the HULL code to verify the estimates made of the response of a water catchment to a series of bullet impacts.

E. RESULTS

The most useful of the earlier Air Force sponsored projects was found to be the KD Engineering study conducted in 1993 which showed the uranium to be concentrated in the large particle fractions (>20-mesh) and to a lesser extent, in the fines (sizes <65-mesh).

The review of uranium mining technology did not reveal any attractive choices since the procedures are based on ore dissolution and reprecipitation, methods which are not applicable to the test site and which, in themselves, generate substantial quantities of mixed waste.

The review of alternative operating procedures and/or alternative catchment media did not reveal any promising choices for implementation at the present test site.

The results of the sampling analysis confirmed the earlier work reported in the KD Engineering study. This analysis indicated that about 62 percent of the depleted uranium is contained in the coarse fraction, (> 10-mesh) and approximately 18 percent in the fines fraction, (< 60-mesh). Thus removal of these two fractions will remove about 80 percent of the depleted uranium.

Sieving practice at the gun test site and other depleted uranium concentration data support these findings. Sifting through 1/2 inch-opening screens at the gun test site recovered an average of 76 percent of the depleted uranium fired into the butt in the period between January 1979 and February 1982.

Size distributions of sand obtained from suppliers near Eglin AFB indicates that pre-sifted sand, which is available for a small cost penalty, consists largely of particles in the -10/60-mesh range. only about 83 percent of the unsized sand falls within these limits.

Wet separation methods were also judged to offer promise for effective separation but require a water handling system which entails an added cost penalty, especially if there is a chance for water contamination in excess of 40 pCi/mL.

F. CONCLUSIONS

Several potentially attractive methods for separating the depleted uranium sand were identified but need to be subjected to an economic analysis and feasibility review to determine the method of choice. Regardless of the final selection, the use of presized sand in the target butt will allow a substantial saving in the amount of material which must be discarded and sent for storage along with the depleted uranium.

G. RECOMMENDATIONS

Presized sand should be used in the target butt to allow a substantial savings in the amount of material that must be discarded.

The wet separation methods should be subjected to further analysis to determine their technical feasibility and relative economics.

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SECTION I
INTRODUCTION

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This report provides a description of Phase 1 activities of the project entitled "Catchment and Separation of Depleted Uranium Projectiles," as specified by USAF Work Order No. W014895D. Phase 1 activities, described in the Statement of Work, deal with an evaluation of the system operations and potential for improved uranium separations methods that would reduce disposal costs of contaminated sand.

B. BACKGROUND

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Specifically, Phase 1 activities include: (1) a literature review and evaluation of improved methods for separating uranium from sand, (2) a review and evaluation of previous , related studies sponsored by the Air Force Engineering Services Center (AFATL), (3) a review and documentation of uranium mining technology with a view toward application at the gun test facility, (4) a sampling and analysis of the contaminated sand in the butt, (5) description of methods for improved uranium separation from sand which would lower disposal costs of contaminated sand, and (6) an evaluation of alternative bullet-stopping media for inherently better uranium separation.

SECTION II
OPERATION OF THE AMMUNITION AND GUN TEST FACILITY

A. PURPOSE AND SCOPE OF USE FOR THE C-64 AREA TEST BUTT

As part of an ongoing quality assurance program, Air Force ammunition from storage is sampled periodically for test firing to assure that it is in field-ready condition. The test site under consideration, designated TA C-64 at Eglin Air Force Base, Florida, provides for the test of the Air Force Gun, Automatic Utility-8 (GAU-8), which fires 30-mm armor-piercing-incendiary (API) ammunition, the primary constituent of which is DU. Figure 1 is a plot of the test area showing the gun test building, gun butts, and nearby radioactive storage areas. Projectiles are fired by a Gatlin-style, seven-barreled gun mounted in a fixed position inside the building on this site. At high rate, 4200 rounds/min are fired, corresponding to 10 rounds/s for each of the seven gun barrels. The capacity of the magazine is 1350 rounds; however, to date, the maximum test duration has been 3 seconds, during which about 210 rounds were fired. Projectiles are fired through an open door, in the test building, through two light screens that measure the projectile velocity, through an electronic location (x-y plane) sensing device, and into a dampened sand butt.

B. PHYSICAL DESCRIPTION OF TEST BUTT AND CATCHMENT MATERIAL

Washed, unsized, local river sand is used to stop the rounds fired by the gun from a distance of ~100 feet. The target building consists of a concrete structure of 20 feet interior width at the front and narrowing to 15 feet at the rear. A photograph of the target building, showing the bullet entry port, is shown in Figure 2. The butt is 45.5 feet long and 20 feet high, with the floor sloping toward a trough in the rear. The walls are made of reinforced concrete that is 1.5 feet thick on the sides, 1 feet thick on the top, and 2 feet thick on the back wall. The front panel is made of 1-inch thick, 4- by 8-feet plywood sheets with a 6-foot-diameter hole for bullet entry. The front panel is side-hinged to allow complete opening for access to the sand by a front-end loader. Removable steel bars prevent the doors from swinging open prematurely. General butt dimensions and some construction details are included as Figure 3. A 5000-ft^3/min filter system, consisting of an inlet area with deflection vanes, a prefilter, and a HEPA absolute filter, is located on the top of the test butt. Air from the butt is drawn continuously to the filter during firing to reduce contamination of the area in front of the butt.

The test butt contains about 280 yd^3 of sand piled highest in the back center, sloping down slightly on the sides, and sloping to the concrete base a few feet from the front wall.

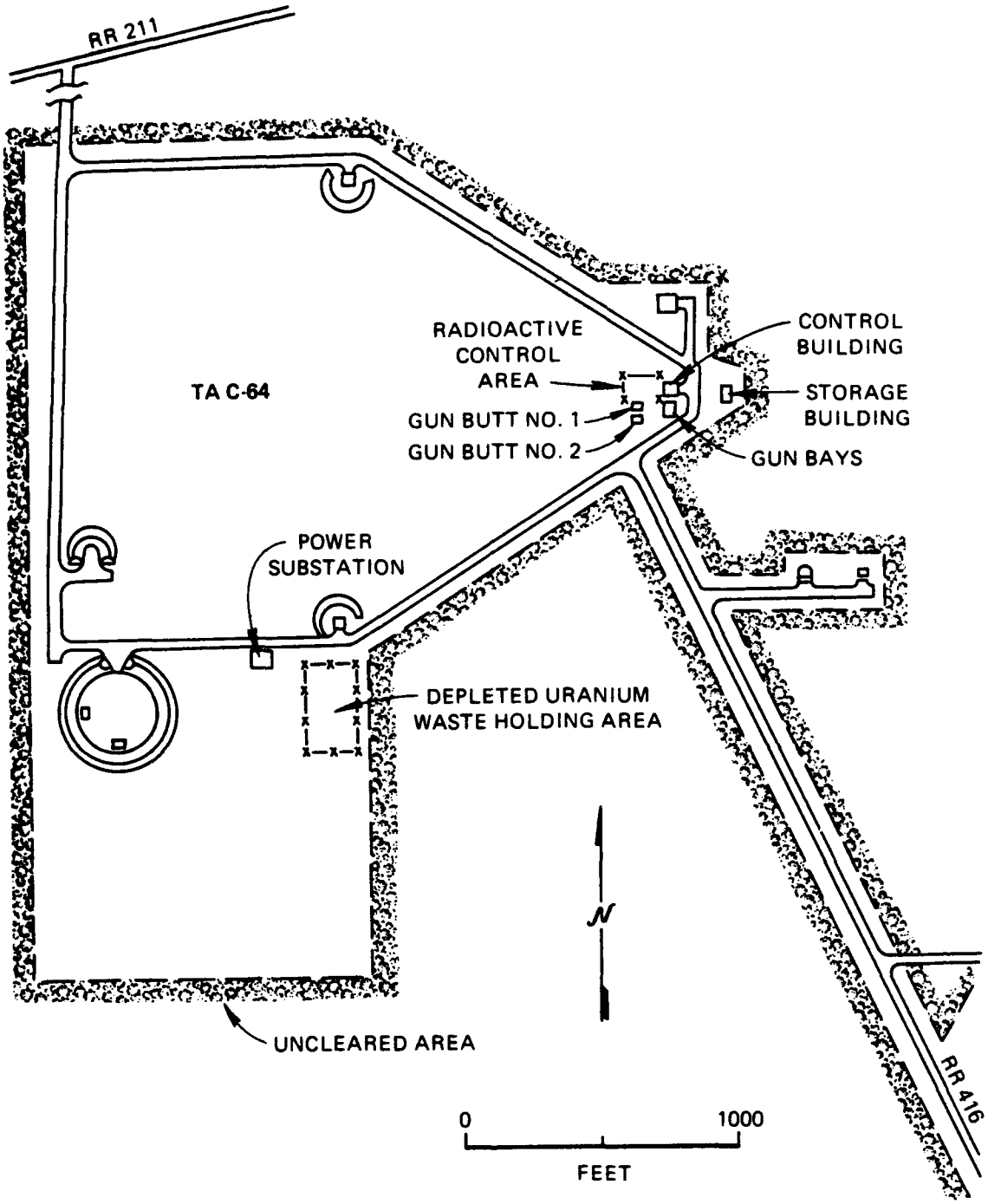

FIGURE 1. Plot Plan of Gun Test Facility TA C-64.

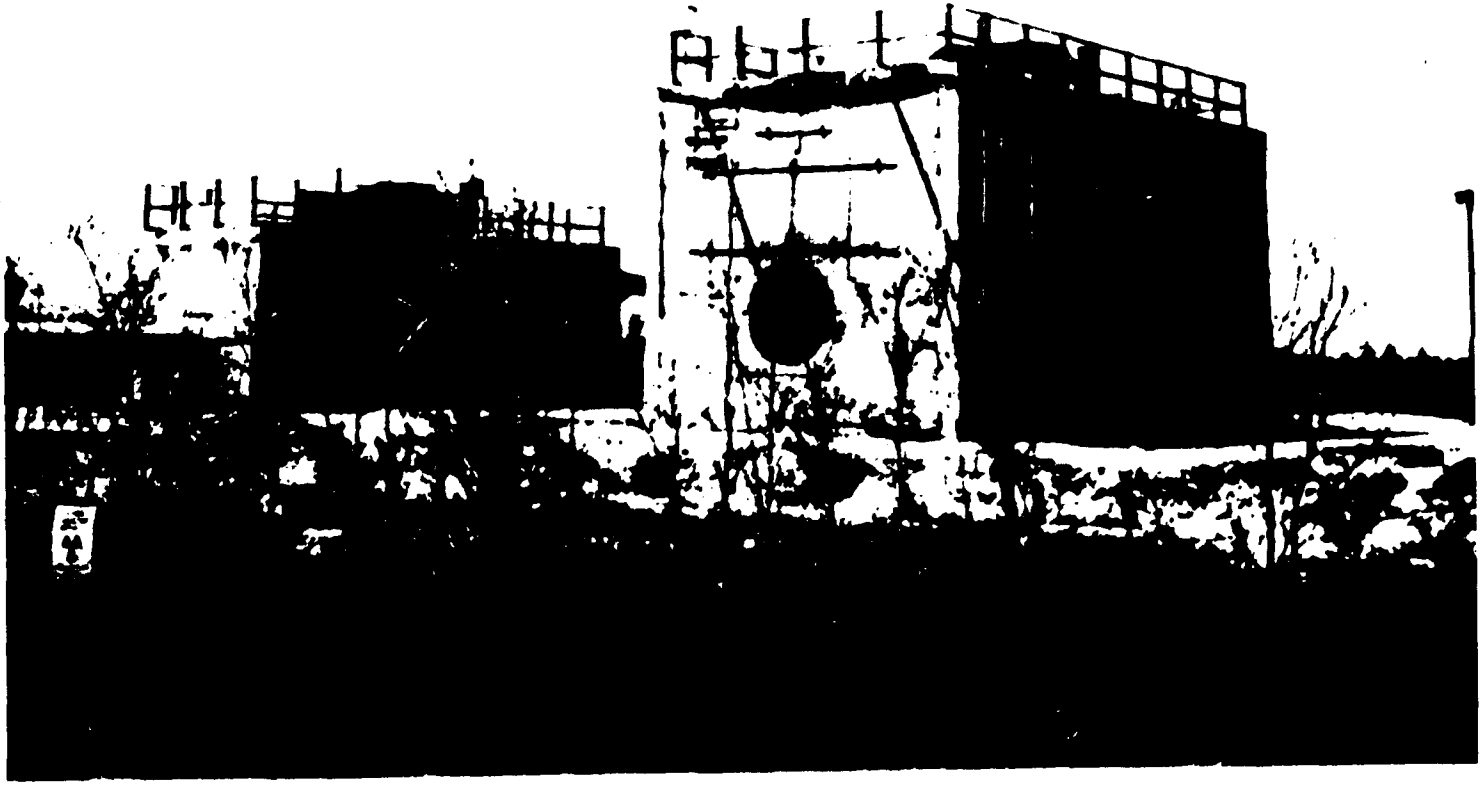

FIGURE 2. View of Target Area 64 Catchment Building.

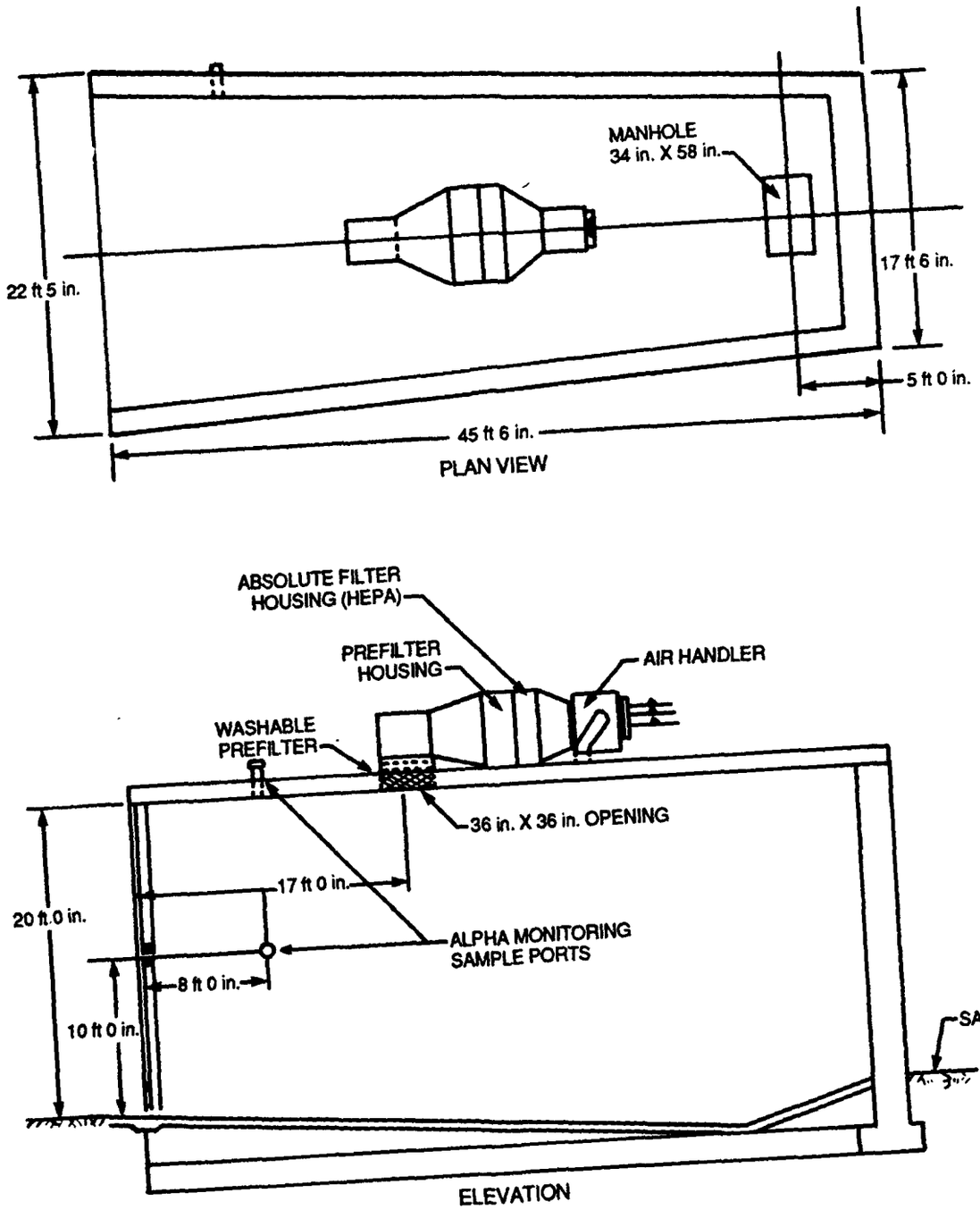

FIGURE 3. Plan and Elevation of Target Building.

An outline of the test bullet is shown in Figure 4, illustrating the 30-mm-diam aluminum windscreen, which departs on impact, the approximate shape of the DU penetrator, and the plastic assembly that provides rotation. The mass of DU per bullet is ~0.3 kg and may contain a small degree of alloying metal (e.g., aluminum or titanium).

C. TARGET OPERATING PROCEDURES

Table A-1, Appendix A, provides monthly record of target test firings and associated mass of DU from test operations from January 1979 through June 1988[1]. The target sand is periodically removed and treated because of the accumulation of projectile fragments; this presents an increasing operational hazard because of the potential for ricochet. Sand removal and treatment operations are of two types: (1) sand removal using a front-end loader, sifting through a 1/2-inch-opening sieve to collect projectile fragments, the sand being returned to the target and (2) sand removal, storage on-site in drums, and replacement with fresh sand in the target.

A summary of target testing and cleanout operations is presented in Table 1.

TABLE 1. SUMMARY OF TARGET OPERATIONS THROUGH JUNE 1988

	Firings between target cleaning dates				
Date of target cleaning	Cleaning operation	Rounds	DU mass(kg)	Date shipped from EAFB	Mass of DU captured by sifting (kg)
April 1979	a	6,453[b]	1,932[b]	July 1980	1,450
October 1979	a	7,416	2,219	July 1980	1,532
January 1980	a	11,239	2,779	July 1980	1,443
July 1980	c	11,423	3,373	February 1987[d]	
November 1980	a	20,268	6,067	October 1981	4,724
February 1982	a	27,321	8,180	May 1983	5,230
March 1984	c	25,295	7,050	February 1987[d]	
April 1986	a	24,243	7,271	(Not yet shipped)	
May 1987	a	23,307	6,994	(Not yet shipped)	
June 1988	None	5,729	1,719	(DU in butt)	

[a]Sand removed, sifted through 1/2-in. sieve. Sand returned to butt.
[b]From start of tests in January 1979 through April 1979.
[c]All sand removed and stored in barrels. Fresh sand placed in butt.
[d]Stored sand plus DU repackaged and shipped to Barnwell, S.C., for permanent storage.

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[1]H. C. Harris, Eglin Air Force Base, personal communication, 1988.

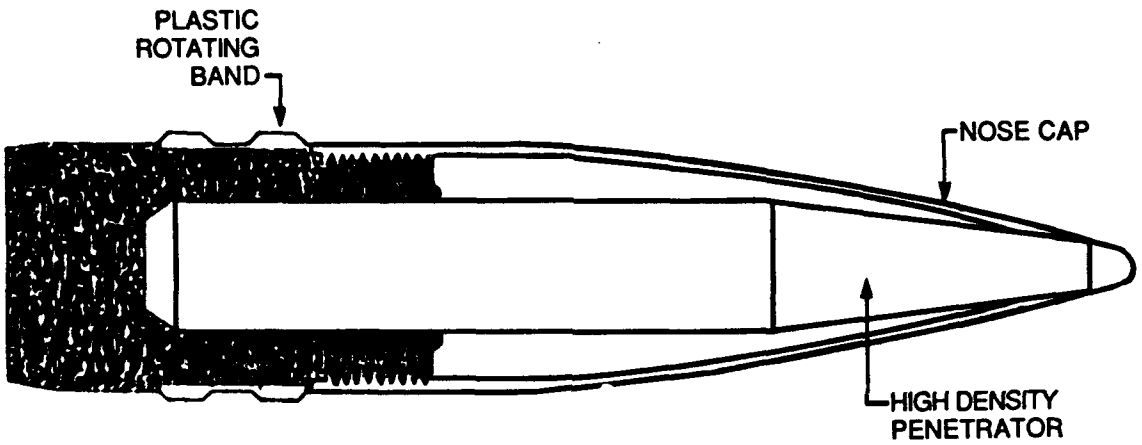

FIGURE 4. 30-mm Armor Piercing Projectile High-Density Penetrator.

As shown, the initial cleanout operation was conducted in April 1979 following the firing of 6453 API rounds containing 1932 kg DU from test initiation in January 1979. This initial cleanout involved sifting through 1/2-inch mesh openings, capture of about 1450 kg DU (or 75 percent of the total DU), with the sifted sand containing about 486 kg of DU, which was returned to the target. As the table shows, two additional similar cleanout and sifting operations took place in October 1979 and January 1980. A total of 4425 kg of DU fragments were captured by these three initial sifting operations, which represented about 59 percent of the total uranium fired. The uranium fragments were stored onsite until July 1980, at which time they were shipped to permanent storage at the Barnwell, South Carolina, burial facility. The first complete sand replacement operation occurred in July 1980, when all the sand removed from the target was stored onsite in 55-gallon drums and fresh sand was placed in the target. As Table 1 shows, the contaminated sand was stored onsite until February 1987, when it was repackaged and shipped to Barnwell for permanent burial. This shipment also included contaminated sand obtained from the second cleanout operation, which occurred in March 1984.

In August 1988 the target sand contained small DU fragments, which were the residue of two sifting operations that took place in April 1986 and May 1987 and projectile fragments from subsequent test firings.

D. REQUIREMENTS AND RESTRICTIONS

Because of the uranium in the sand, the material removed from the test butt is categorized as a low-level radioactive material; however, it is not classed as chemically hazardous [or Resource Conservation and Recovery Act (RCRA) waste], which would require more restrictive handling. Permit number 09-30031-1AFP grants to the Armament Division (AD) of Eglin Air Force Base permission to receive, possess, and store radioactive materials, including DU, for the purpose of testing and evaluating munitions containing DU and high explosives with no more than 90.9 kg (200 lb) explosive weight per test sequence. A maximum of 80,000 kg of DU in any form is permitted on base at a given time.

Various federal regulations govern the use, storage, disposition, and exposure to nuclear source materials. The Atomic Energy Act of 1954, the Energy Reorganization Act of 1974, the Department of Energy (DOE) Organization Act of 1977, the Uranium Mill Tailings Control Act of 1978, and the Nuclear Waste Policy Act of 1982 pertain to the federal responsibility for control of nuclear materials. According to the permit issued to AD of Eglin Air Force Base by the U.S. Air Force (USAF) Radioisotope Committee under authority of U.S. Nuclear Regulatory Commission (NRC) License No. 42-23439-01AF, the applicable regulations include Title 10, Section 1, Code of Federal

Regulations (CFR), Part 19, "Notices, Instructions and Reports to Workers; Inspections," Part 20, "Standards for Protection Against Radiation," Part 40, "Domestic Licensing of Source Material," and T.O. 00-110N-4, "Acquisition, Use, Storage, and Disposition of Nuclear Source Material."

Material shipping and handling restrictions also include Department of Transportation (DOT) restrictions on shipping hazardous materials. A comprehensive exposition of the impact of NRC and DOT regulations on test operations and waste material shipping procedures in effect in 1984 has been provided in Reference 1, a study by the Westinghouse Hittman Associates sponsored by the Air Force.

1. Operational Restrictions

In summary, the following operational restrictions exist:

a. Test hazards and damage to the target building are held to an acceptably low level by periodic removal of the large bullet fragments from the butt. As seen in Table 1, removal of the large bullet fragments is required after firing from 20,000 to 27,000 rounds.

b. Proper operation of the filtration system on the target building roof during firing tests requires periodic elimination of fine dust generated by bullet impacts in sand. Currently, this is controlled by periodically replacing all the target sand, as has been done thus far on two occasions. The fines tend to clog the filters in the air exhaust system, which is required to maintain negative building pressure during test firings.

c. The NRC license limits the amount of DU onsite to 80,000 kg, including the fragments in the butt, stored waste material onsite, and munitions for future tests. However, this limitation has not been a controlling factor in testing operations.

E. DISPOSAL OF URANIUM-CONTAMINATED SAND IN 1987

In February 1987, contaminated sand from the 1980 and 1984 total test butt cleanouts were sent to Barnwell, South Carolina, an approved commercial low-level radioactive waste disposal site, for burial. The total cost of disposal was $2.8 million, including environmental assessment, repackaging, transportation of 26,850 feet^3 of material, and burial fees at the commercial facility. The disposed material was predominantly sand containing 12,248 kg uranium, packaged in ~3500 55-gallon drums. Included also were 58 17-gallon drums containing spent round fragments, ~100,000 pounds of steel plates used in experiments,

and 117 55-gallon drums of miscellaneous material (contaminated filters, clothes, crates, pallets, and wooden boxes).

Repackaging of the contaminated sand into new 55-gallon drums was required since the original drums had rusted. Cement was used to solidify the wet sand. Container lids were left unsealed to allow the escape of hydrogen gas produced by the chemical reaction of DU with water and concrete. Appropriate precautions were taken to prevent gas explosion.

SECTION III
EARLIER STUDIES SPONSORED BY THE AIR FORCE ARMAMENT LABORATORY

A. WESTINGHOUSE HITTMAN STUDY

Westinghouse Hittman Nuclear, Inc., was contracted to evaluate various disposal options for uranium contaminated sand from the target butt (Reference 1). These options included:

- Disposal at DOE facilities,
- Disposal in commercial facilities,
- Onsite disposal in an engineered burial facility.

1. Disposal at DOE Facilities

Transportation and burial costs (i.e., excluding packaging and preparation) were estimated for disposal of a 3500-drum inventory at the Nevada Test Site and at Oak Ridge, Tennessee. The latter site, however, was probably not a practical alternative because of its small size. Costs for the Nevada site were estimated at $238,000 for transport and $66,000 for burial, for a total cost of $304,000 and a unit cost of $11.57/feet^3 of waste material.

However, a Memorandum of Understanding between Department of Defense (DOD) and DOE precluded use of DOE burial facilities if commercial sites were available. This was a significant factor at the time of the study (1985) since at that time a regional compact restricted use of the nearest commercial facility at Barnwell, South Carolina However, such regional compacts are no longer in effect.

2. Disposal at Commercial Facilities

As noted above, there are no longer any restrictions regarding the use by the DOD of the nearest commercial radioactive burial facility at Barnwell, South Carolina, as was in existence at the time of this study. Disposal costs at the Barnwell facility for a 3500-drum inventory were estimated at $72,000 for transportation and $669,000 for the burial fee, for a total cost of $741,000 and a unit cost of $28.41/feet^3 of waste.

A major factor in the use of commercial facilities is the selection of appropriate packaging that satisfies DOT and NRC regulations. Extensive discussions on this subject are presented.

3. Onsite Disposal in an Engineered Facility

One advantage of this approach is that it saves the large transportation costs associated with off-site burial. In addition, higher radioactive concentrations may be disposed of in this fashion relative to unrestricted disposal onsite. According to judgments and evaluations presented in Reference 1, radioactivity levels of up to 3000 pCi/g insoluble and 1000 pCi/g soluble may be buried in a licensed, engineered site, compared to 35 pCi/g for unrestricted disposal onsite.

Extensive descriptions are provided for several alternatives for onsite burial. Unit costs for an "above-ground vault," the lowest cost of the ten options considered, were estimated at $\$40.03/feet^3$ of waste material, substantially higher than for either mode of off-site disposal.

4. Alternative Catchments

Some consideration was given to means for using a water catchment, which, if feasible, would eliminate disposal problems by allowing complete uranium recovery for recycle. However, the two concepts presented would be difficult to implement. One version entailed use of an elevated platform for the gun, firing downward at a water pool. However, unless the firing angle were quite steep (greater than ~45°), one may expect some unknown fraction of the incident projectiles to be reflected from the surface. A second suggested concept involved use of a metallic deflector altering a horizontal trajectory downward toward a water pool. However, such a deflector would shortly be deformed by projec .les, leading to an unpredictable behavior following the initial projectile contact.

A third advanced concept entailed use of a sand catchment containing a 6-feet-diam steel pipe down its center. The pipe would reduce (but not eliminate) the contamination rate of the major mass of the sand exterior to the pipe. Although this concept may prove to have merit, intuitively, one feels that it is not worth the trouble. At any rate, evaluation of this concept was presented in association with an engineered, onsite burial facility, which, it has been decided, will not be fabricated.

5. Leaching of Uranium from Sand

Information presented in Reference 1 on the transport of uranium through soil provides an insight regarding the possible radioactivity levels in waste waters from wet separations methods. According to this reference, uranium present initially as the metal gradually oxidizes to an insoluble UO_2 form, which, in turn, oxidizes further to the hexavalent uranyl ion UO_2+2, which is the principal form contributing to the overall uranium

solubility. The degree of gradual transformation to this soluble form from the metal depends on the ambient oxidizing conditions (usually, degree of aeration) and the acidity. Test data indicate that uranium solubility by this means can range from about 0.2 mg/L at pH = 6.1 to 0.7 mg/L for a more acidic solution of pH = 5.7.

The presence of carbonates can profoundly increase the solubility of uranium. Carbonates could either be present in the sand as limestone impurities or may be gradually added as a result of CO_2 dissolution from exposure to air. Test data indicate that, with carbonates present, uranium solubility can reach 2900 mg/L in pH = 5.7 water and 240 mg/L in pH = 6.1 water.

A computer program for calculating equilibrium solubilities of uranium in water as it depends on carbonate level, oxidizing conditions, temperature, and pH level is available at ORNL. However, it is expected that equilibrium levels will be only slowly approached; so actual uranium solubility levels in a sand catchment would be difficult to estimate. Wastewaters drained from contaminated sand have always been measured to contain significantly less than 40 pCi/mL, the upper limit for uncontrolled release.[2]

Nevertheless, at the high solubility level of 2900 mg/L reported for mildly acid water with carbonates present, considerably higher radioactivity concentration than 40 pCi/mL would be present. As outlined in Table 2, the specific activity of pure DU is estimated as 1.13×10^6 pCi/g, depending somewhat on the particular tails composition of the diffusion plant. Thus, the low end of the solubility scale reported in Reference 1, 0.18 mg/L, would result in an activity level of 0.20 pCi/mL, whereas the high solubility end, near 2930 mg/L, would result in a solution activity of 3310 pCi/mL.

A specific activity of $1.13 \times \sim 10^6$ pCi/g for DU would yield a contaminated sand activity of 11,300 pCi/g for a typical 1 percent DU mixture. To achieve 35 pCi/g of contaminated sand, the DU concentration would need to be reduced to 0.0310 mg DU/g.

B. SEPARATIONS TESTS USING JIGGING

An informal report describes the results of uranium separations tests using a mineral ore jig.[3] As described in Section VI, a mineral jig affects a separation basically by gravity difference as the slurry medium is pulsated on a wire

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[2]H. C. Harris, Eglin Air Force Base, personal communication, 1988.

[3]R. C. Crews, Eglin AFB, unpublished report, August 22, 1986.

screen by the action of water jets. Particle size also affects the nature of the separation, and, generally, successful jig operation requires conditions more or less tailor made for the particular feed material. Such was not the case for these tests, wherein the jig tests were performed on a system optimized on a somewhat different feed.

TABLE 2. SPECIFIC ACTIVITY OF DU AND DU SOLUTIONS

	^{234}U	^{235}U	^{238}U
Abundance (at. %)	0.0054	0.72	Balance
Natural			
Depleted uranium (assumed)	~0.0018	~0.25	Balance
Half-life, years	2.44×10^5	7.04×10^8	4.47×10^9
Specific activity, mCi/g	6,270	4.52[a]	1.01[b]
Contribution to DU activity	10.0%	1.2%	88.8%

Specific activity of DU: 1.13×10^6 pCi/g

Activity of water solutions	Concentration (mg/mL)	Activity (pCi/mL)
Minimal solubility[c]	0.18×10^{-3}	0.201
Maximal solubility[d]	2.93	3310

[a]Includes daughter ^{231}Th (25.5-h half-life).
[b]Includes daughters ^{234}Th (24.1 d) and ^{234}Pa (6.70h).
[c]Slightly acid, no carbonates (Reference 1).
[d]Carbonates present, pH = 5.7.

Separations results affected by five successive feed cycles are shown in Table 3. The feed contamination level is not given but is estimated to be ~2000 pCi/g. As seen, the initial two passes resulted in about a factor of 3 radioactivity reduction per pass. Subsequent passes produced much less decontamination, and the level appeared to bottom out at about 90 pCi/g. A level of 35 pCi/g, required for onsite disposal, was the original objective.

Jigging appears to provide significant decontamination of the target sand, but it is probably insufficient for onsite disposal. An optimized jig, selected specifically for the target sand properties, would have likely performed better.

TABLE 3. RADIOACTIVITY REDUCTION DUE TO FIVE SUCCESSIVE JIGGING SEPARATIONS RUN[4]

Cycle	Radioactivity level (pCi/g)
Feed	~2000 (?)
1	744
2	228
3	123
4	112
5	91

In addition to the separations tests, scanning electron micrographs were taken of four sand particles selected by tweezers by virtue of their unusual appearance. The plots clearly showed a thin layer of splattered, metallic uranium on each of these selected grains. The metal was positively identified as uranium by x-ray fluorescence. We do not know to what degree this form of uranium was present in the sample as a whole. However, each such grain would have basically the size and nearly the density of the unused feed sand. Hence, this is a form of contamination that would be difficult to separate by any physical means.

C. K D ENGINEERING COMPANY REPORT

1. Objectives

The K D Engineering Company of Tucson, Arizona, was contracted to evaluate uranium-sand separations procedures with the following specific objectives (Reference 2):

a. identification of separations techniques and equipment,

b. separations tests on a bench scale to evaluate equipment and performance parameters,

c. chemical analysis of feed and product flows, and

d. separations equipment and flow sheet recommendations.

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[4]R. C. Crews, Eglin AFB, unpublished report, August 22, 1986.

2. Target Sand Characterization

The makeup sand used for these tests was determined to have the size distribution shown in Table 4. We note, for this sample at least, that 74 percent of the makeup sand consists of sizes between 420 and 1680 μm (i.e., Tyler mesh range -10 to +35).

TABLE 4. MAKEUP SAND SIZE DISTRIBUTION BY DRY SCREENING (REFERENCE 2)

Size fraction Ranger (μm)	Mesh[a]	Fraction weight (%)	Cumulative weight (%)
>1680	+10	5.37	5.37
841-1680	+20	22.15	27.52
595-841	+28	24.00	51.52
420-595	+35	27.44	78.96
297-420	+48	6.07	85.03
210-297	+65	8.19	93.22
149-210	+100	3.28	96.50
105-149	+150	1.85	98.35
74-105	+200	0.85	99.20
44-74	+324	0.39	99.59
37-44	+400	0.11	99.70
<37	-400	0.30	100.00

[a]Tyler mesh; +10 signifies fraction held up on mesh 10, etc.

Table 5 shows size distribution and analysis of a target sand sample containing 1.99 weight percent uranium. The unused and used sand size distribution listed in Tables 4 and 5 are illustrated in Figure 5, together with the distribution of uranium in each size fraction (shown by the darkened bars). Particles retained on a 1/8-inch sieve, which were probably predominantly uranium metal fragments, were not included in this sample. The major differences in size distribution with respect to the supply sand are the existence of less +35-mesh material and significantly more fines. Uranium is seen to be concentrated in the large (+10-mesh) and small (+400- and -400-mesh) size fractions. Rejection of the +10 and -35 fractions would capture 67 percent of the uranium in this sample in 22 percent of the total mass. Rejection of the fines (-35 sizes) would in any case be desirable for operational reasons.

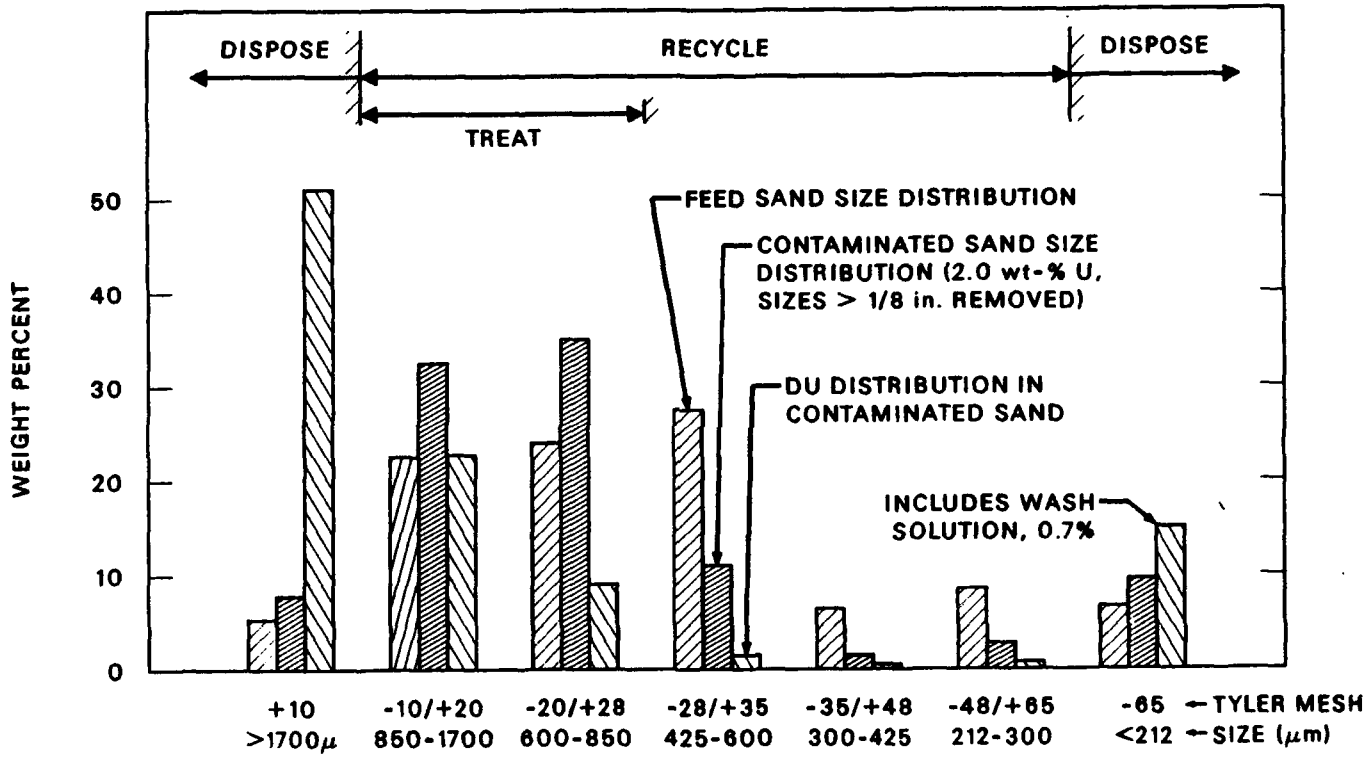

FIGURE 5. Size and DU Mass Distributions (Reference 2).

Note that 14 percent of this sample is termed "soluble," that is, soluble in a pH 7 sodium carbonate solution. This fraction of the uranium is identified as UO_3. The balance consists of uranium metal, U_3O_8, and perhaps uranium silicate. This last material would be contained within the silica grain and thus would be insoluble to nitric acid leaching; aqueous reagents containing HF or dissolution in molten carbonate salt are required for dissolution of uranium silicate.

Other analyses reported by Keane (Table 6) include the 1/2-inch to 1/8-inch size fraction, which was estimated to be 70 percent uranium. (Sizes >1/2 inch were retained by the 1/2-inch screening at Eglin AFB.) Table 5 reinforces the observation that the uranium is concentrated in the coarse and the fine size fractions. In this case, the intermediate fraction from 212-1700 μm (-10 to +100-mesh) contains 74 percent of the sample mass but only 6.7 percent of the uranium. The coarse fractions (+10-mesh) contain 17.2 percent of the sample mass and 90.4 percent of the uranium. The fines, which need to be disposed of for operational reasons, contain 2.9 percent of the total uranium in 8.7 percent of the total sample mass.

TABLE 5. WET SCREEN ANALYSIS OF TARGET SAND CONTAINING 1.99 WT % U, 14% SOLUBLE (REFERENCE 2), EXCLUDING SIZES >1/8 IN.

Size fraction	Wt (%)	Wt % U in each fraction	Soluble[a] (%)	% of total U in each sample
+10	7.86	12.9	10	51.2
+20	32.2	1.34	6	22.5
+28	34.9	0.50	16	8.9
+35	11.1	0.29	22	1.6
+48	1.76	0.17	37	0.2
+65	2.51	0.40	26	0.6
+100	1.16	0.69	19	0.4
+150	1.10	0.82	27	0.4
+200	0.72	1.25	22	0.4
+325	1.00	1.80	23	0.9
+400	0.43	3.02	16	0.7
-400	5.26	4.39	38	11.6
				0.7 (wash)
Total	100.0			100.0

[a]Soluble in sodium carbonate solution, that is, UO_3.

TABLE 6. URANIUM DISTRIBUTION IN FOUR BROAD SIZE FRACTIONS, INCLUDING THE 1/2 TO 1/8 SIZE RANGE, FOR TOTAL URANIUM OF 8.9 WT % (REFERENCE 2)

Size fraction		Percent U in Wt		
Mesh	μm	(%)	Fraction	
1/2 to 1/8 in.	3,175-12,700	10.2	-70	80.3
1/8 in. to +10-mesh	1,700-3,175	7.0	12.9	10.1
-10 to +100-mesh	212-1,700	74.1	0.8	6.7
-100	<212	8.7	3.0	2.9
		100.0		100.0

3. K D Engineering Separations Tests

a. Dry Separations Tests

(1) Dry Magnetic Separation. No magnetic material was separated using a Carpo Laboratory Electromagnetic Separator.

(2) Electrostatic Separation. Tests were performed on several sized fractions using an unspecified device in which the metallic uranium particles were attracted to wire electrodes. The entire sample was fed onto a rotating, grounded, brass drum, which retains the balance of the material. The evaluation states that electrostatic separation shows best results for classified size fractions. Their experience was that excessive dust was produced for the smaller sizes, that is, -20-mesh (<850 μm), but fairly good results were obtained for the -10/+20-mesh fraction, as shown in Table 7. The table shows that 96 percent of the uranium in this fraction was captured in a stream consisting of 43 percent of the total mass. (It is worth noting that the -10 to +20-mesh size is one of the principal size fractions of the feed sand; see Table 4). As indicated, the uranium in this fraction represents 70 percent of the total uranium in the four fractions; -10/+20, -20/+35, -35/+100, and -100/+200 (not shown in the table).

b. Wet Separations Tests

(1) Wet Magnetic Separation. No separation was achieved using a Davis Tube Wet Magnetic Laboratory Unit.

(2) Jigging. A jig is a device that separates solid mixtures by utilizing differences in the abilities of grain to penetrate a shaking bed. A liquid jet pulsates the bed, causing the heavier material to work its way down while the lighter material rises to the top. Tests were performed

TABLE 7. ELECTROSTATIC SEPARATION TESTS FOR THREE SIZE FRACTIONS (REFERENCE 2)

Size fraction	Stream	Feed (wt%)	Total sample (wt%)	DU in stream stream	% of total U in sample	U% of total
-10/+20	Anode	43	10.3	96.4	70	
	Drum	57	0.30	3.6		
	Feed	100	4.64	100		27
-20/+35	Anode	1.7	9.0	33.3	4.4	
	Drum	98.3	0.30	66.7		
	Feed	100	0.45	100		52
-35/+100	Anode	0.32	23.2	9.77	0.7	
	Drum	99.7	0.70	90.3		
	Feed	100	0.76	100		15

using a 4- by 6-inch Denver Mineral Jig, the results of which are given in Table 8. No mention is made regarding the feed material for this test, that is, whether it was one of the classified portions of the total sample or a portion from the sample as a whole. Since jigging results appear to be difficult to predict and the procedure needs to be optimized for a particular set of feed characteristics, the absence of feed characterization renders these results difficult to evaluate. Table 8 shows that jigging concentrated uranium in the bed, for this sample; however, only 26 percent of the total uranium in the feed was thereby removed. Combining the hutch and bed streams would remove 81 percent of the uranium in the feed in 34 percent of the total sample mass.

TABLE 8. JIGGING SEPARATIONS TEST RESULTS ON UNSPECIFIED FEED FRACTION (REFERENCE 2)

Jigging stream	Stream (wt%)	U core in stream (wt%)	% of U in stream
Hutch screen	31.4	2.9	55
Bed	2.5	17.3	26
Tail	66.1	0.49	19
Total	100	1.67	100

(3) Shaking Table. This is a gravity separations device which, according to Reference 2, is best suited to "top size limited" fractions. Accordingly, a Wilfley Laboratory Shaking Table was used for tests on a +10-mesh size fraction. (Though not explicitly stated, this appears to be the 1/8-inch/+10-mesh fraction cited in Table 6.)

Interpretation of the reported shaking table test results is unclear because of apparent inconsistencies in the reported mass balance. However, it is stated that the 1/8-inch/+10-mesh size fraction containing 18 weight percent uranium yielded a stream concentrate containing 48 percent of the fed uranium. (This does not appear to be supported by the tabulated data.) In addition, large quantities of water are required for table operation, which would require storage and some treatment prior to disposal.

(4) Static Belt Separation. This device is an inclined sluice with a highly textured surface that serves to capture the heavy particles from a flowing slurry. The heavy particles are removed on a batch basis. Separations tests were conducted on the >850-μm size fraction (i.e., evidently the +20-mesh fraction of Table 5, which excludes sizes >1/8 inch), which reportedly contained 4.3 percent uranium and comprised 33 percent of the original feed mass.

Reportedly, a concentrate was produced consisting of 20 percent of the unscreened feed mass. Reported results are difficult to interpret because of apparent inconsistencies between the text and tabulated values. Evidently, some concentration was achieved. Large amounts of water required for operation would need to be stored and possibly treated prior to disposal.

(5) Moving Belt Separation. This separation device consists of an inclined moving belt upon which the slurry flows countercurrently downward. A highly textured surface captures the high-density particles that are continuously removed by means of water jets. Tests using small particles, the <850-μm fraction (-20-mesh), produced a concentrated product consisting of 52 weight percent uranium within 14.4 percent of the total feed mass. The results are reproduced in Table 9.

TABLE 9. MOVING BELT SEPARATOR TESTS ON -20-mesh FRACTION (REFERENCE 2)

Stream	Stream mass (%)	Concentration of U in stream (%)	U distribution (%)
Concentrate	14.4	1.0	52
Tails	85.6	0.16	48
Feed	100	0.29	100

(6) Rotating Spiral Concentrator. This device consists of a disk with a peripheral rim with an axis of rotation inclined from the vertical. The disk has a hole in the center and a spiral riffle that decreases in curvature from edge to center. In operation, heavy materials migrate to the center hole and collect as concentrate.

It is stated that performance improves if the coarse sizes are removed (i.e., "top-size limited"). Therefore, tests were performed on the <1700-μm fraction (-10-mesh), which contained 0.71 weight percent uranium, representing 0.71 percent of the total sample uranium. (As with all the other tests, this excludes sizes >1/8 inch)

The rotating spiral produced a small concentrated mass flow from this fraction containing 62.7 weight percent uranium, representing 36.3 percent of the uranium feed. It is stated that this device may hold promise for the production of high grade uranium product from the -10-mesh material.

Results are summarized in Table 10. Although this device produces a concentrated feed, it is noted that only 36 percent of the fed uranium is captured in the concentrate. While a good product is made, the feed concentration of 0.71 weight percent uranium is reduced only to 0.45 weight percent. In addition, the large amounts of water required for operation may need to be stored or treated prior to disposal.

TABLE 10. ROTATING SPIRAL TEST RESULTS FOR -10-mesh FEED (REFERENCE 2)

Stream	Wt % of stream	U concentration in stream (wt %)	% of fed U in stream
Concentrate	0.41	62.7	36.3
Tails	99.6	0.45	63.7
Feed	100	0.71	100

c. Chemical Separations Studies by K D Engineering

(1) Alkaline Leach Studies. A maximum of only 20 percent of the fed uranium was dissolved from the <425-μm size fraction (-35-mesh) using various alkaline leach reagents.

(2) Acid Leach Studies. The most aggressive acid leach reagent, consisting of nitric acid with sodium chlorate oxidant, resulted in 78 percent dissolution of uranium from the feed (presumably the same -35-mesh material as above).

It was concluded that physical separations methods are preferred to the leaching methods tried because the aggressive reagents required would pose a handling problem.

4. Uranium Separations Scheme Proposed by K D Engineering

The uranium separations scheme proposed by K D Engineering and shown in Figure 6 was reconstructed from the text because the figure was missing; hence, the figure may vary somewhat from the actual recommendation. Basically, a size separation is recommended, enhanced by a gravity device for the -10/+65-mesh fraction. According to test data, about 40 percent of the uranium fed to the spiral classifier would be removed in a highly concentrated residue.

The proposed system is fairly complex, involving eight pieces of equipment, excluding pumps and valves. On the other hand, all components are standard, proven items. This system appears to effect an efficient uranium separation, enabling uranium recycle and producing a relatively small volume of waste.

Simplified versions of the proposed scheme could also be considered. First, the Heavy Media Separator could be eliminated; this separation step could be performed later at a uranium recycle plant. A further simplification would be the elimination of the spiral classifier, which may not be cost-effective. An attendant result would be a reduction of the required water supply. This simplified system is illustrated in Figure 7. Both these schemes may be considered as improvements of the current method.

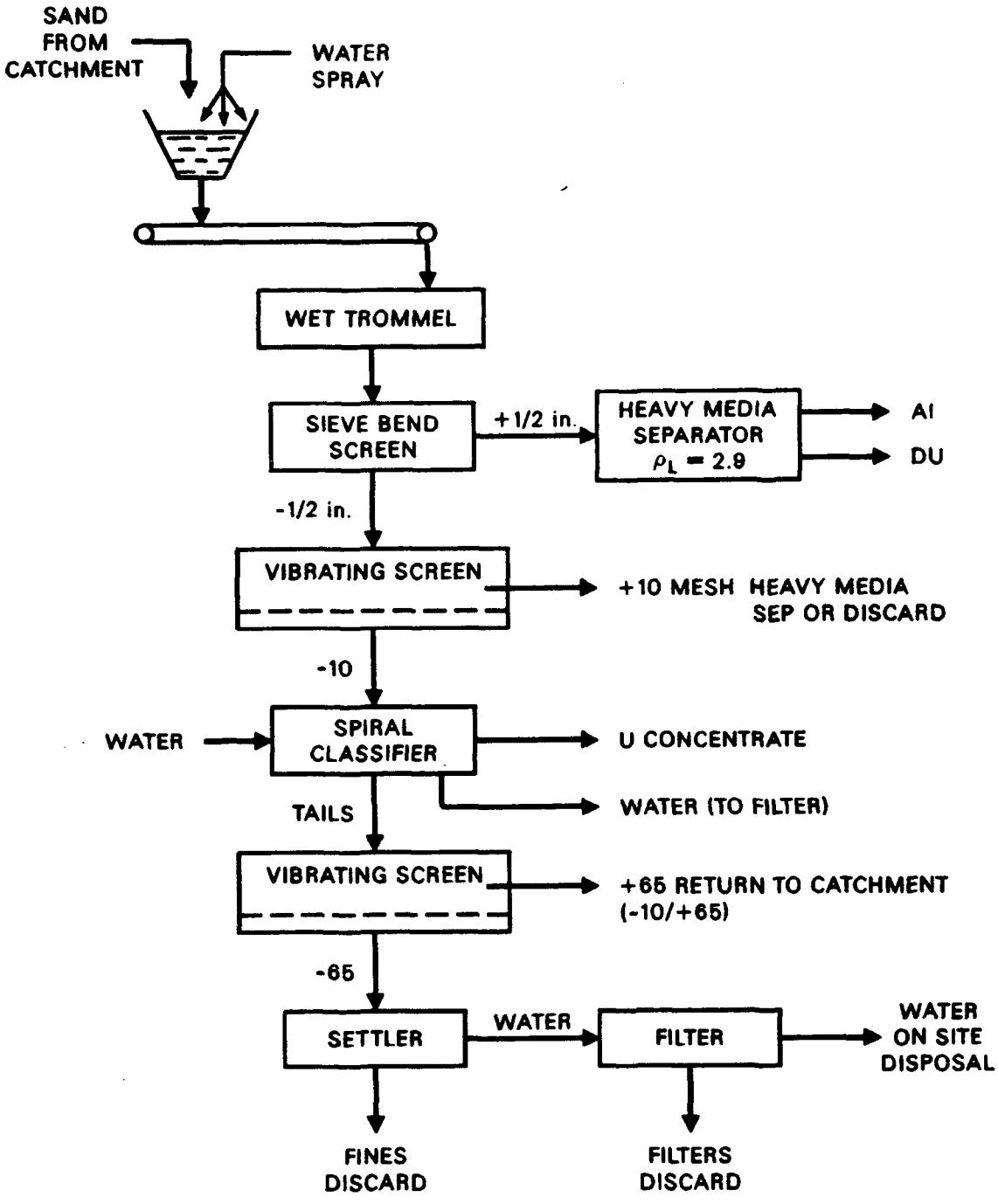

FIGURE 6. Flow Sheet Proposed by K D Engineering (Reference 2).

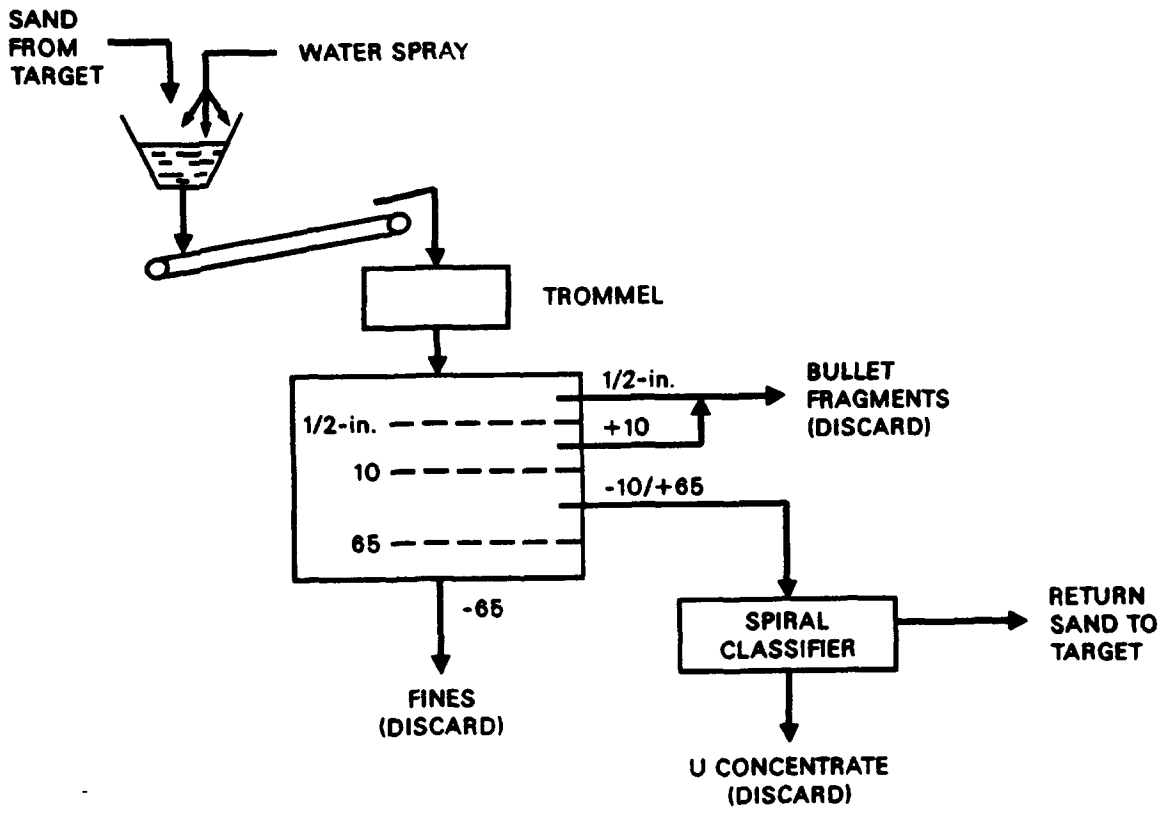

FIGURE 7. Simplified Separations Scheme; Adapted from Reference 2.

Both related schemes use wet separations methods that generate various amounts of wastewater. The experience at the gun test facility, wastewaters would be expected to contain much less than the 40 pCi/mL level, which is the upper limit for onsite disposal.[5] Past experience has demonstrated that settling for ~24 hours suffices to bring concentration levels to well below this limit.

D. FILTRATION SYSTEM FOR REMOVAL OF DEPLETED URANIUM FROM WATER

1. Objectives and Scope

The objective of this study (Reference 3) was to demonstrate methods of microfiltration of uranium- contaminated water generated during munitions tests at Eglin AFB and to determine the resulting degree of radioactivity reduction in the water. Large quantities of uranium-contaminated water are generated at Eglin AFB, with radioactivity levels ranging from 0.09 to 25 pCi/mL. The radioactivity is supposed to be the result of suspended, submicron-sized particulates and is therefore amenable to reduction by micropore filtration. Onsite disposal of the contaminated water would require radioactivity reduction to 40 pCi/mL for compliance with the 10 CFR 20 standard.

TTI Engineering of Norwood, Maine, fabricated and tested a pilot-scale microfiltration system to compare the effectiveness of three cross-flow membrane modules for radioactive decontamination (Reference 3).

2. Filtration Tests

The following three cross-flow membrane filtration modules were tested:

- A/G Technology #CPF-1-E-55, 0.1-mm pore size,
- ENKA #MDO80TP2N, 0.2-mm pore size,
- ALCOA Membralox #1P19-40, 0.1-mm pore size.

Contaminated water was roughly simulated by adding U_3O_8 (of unspecified particle size and enrichment) to local well water and allowing the larger particles to settle.

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[5]H. C. Harris, Eglin Air Force Base, personal communication, 1988.

3. Test Results

The design and operation of the pilot system are described in detail to allow fabrication of a larger unit of this type if such were needed. However, the test results, summarized in Table 11, are inconclusive. It appears that the feed material was not prototypic; adding unspecified U_3O_8 powder to Maine well water appears not to have replicated the Eglin AFB wastewater in that contamination levels in the feed are too low. The decontamination levels achieved are quite small; however, at these very low levels, the observed reduction could be the result of surface adsorption as well as filtration.

TABLE 11. DECONTAMINATION TESTS BY MICROPORE FILTRATION (REFERENCE 3)

Filter	Filtration stream	AFATL/DOE[a] (pCi/mL)	CMI[b] (pCi/mL)
ENKA	Feed	9.97	4.9
	Permeate	7.31	4.1
	Concentrate	4.47	4.3
A/G	Feed	9.55	5.8
	Permeate	6.26	4.5
	Concentrate	19.46	10.2
ALCOA	Feed	6.26	3.9
	Permeate	4.09	4.5
	Concentrate	5.10	10.2

[a]By low background beta counting.
[b]By calculation from uranium concentration determined by plasma spectroscopy.

E. MAGNETIC SEPARATION STUDY

An unpublished report by Martin Marietta Energy Systems, Inc., describes the results of uranium separation tests performed on sand from the C-64 Test Butt using magnetic separation.[6] A bench-scale unit from Frantz Magnetics, Inc., was used in the experiments. In these tests the magnetic gradient was obtained from specially shaped pole pieces rather than by using a magnetized matrix. Air-dried sand was fed through a funnel onto a vibrating tray through which a magnetic gradient was passed. The paramagnetic particles (those with an overall positive magnetic susceptibility such as uranium and most uranium

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[6]J. M. Hoegler, "Magnetic Separability of Uranium from Sand," unpublished ORNL report to Eglin AFB, 1987.

compounds) are drawn toward the area with the highest magnetic field intensity, while the diamagnetic particles (those with an overall negative magnetic susceptibility such as silicon and many silicon compounds) are repelled by the area with the highest magnetic field intensity. Since the magnetic susceptibility of a particle is a combination of the susceptibilities of the components of the particle, particles within a sample possess a spectrum of susceptibilities ranging from pure DU to pure sand. Therefore, if a concentration of one of the components in one of the product fractions is chosen as the independent variable, the concentration of that component in the other product fraction and the quantity of each fraction that can be achieved are dependent variables.

The degree of separation of the uranium from sand is dependent on the extent of the attachment of the uranium to the sand. It appears that separation of uranium from the test butt sand is excellent for this application. The results shown in Table 12 relate to feed that is sized to pass through a 30-mesh sieve and be retained on a 100-mesh sieve. This feed resulted in a product consisting of 98 percent of the feed sand decontaminated from 1.3 percent uranium by weight to a concentration of 0.42 percent uranium by weight. That is, 70 percent of the uranium was removed in 2 percent of the material. Material sized 100 by 200-mesh was decontaminated to approximately the same level. These separations were achieved with one pass. Additional passes were used to improve decontamination, although for a smaller fraction of the feed. Heating the sample to oxidize any uranium metal present prior to separation significantly improved the separation. Here, 81 percent of the uranium was removed in 3 percent of the material.

F. DU CLEANUP STUDY BY LOS ALAMOS CONSULTANTS

The objective of this work, reported in Reference 4, was to devise leaching procedures to clean target sand down to background levels, to <35 pCi/g, an activity level allowing unrestricted onsite disposal. The following procedure was devised and tested, and the description is taken directly from this report summary:

1. Sieve to separate pebbles, aluminum, and fragments of DU from the sand and to remove fines for disposal.

2. Separate the DU fragments from the pebbles and aluminum so the DU can be recycled.

3. Wash the sand with 1/1 water/nitric acid (to dissolve DU fines and corrosion products) followed by water washes to remove acid (for recycle and possible DU recovery).

TABLE 12. MAGNETIC SEPARATION OF URANIUM FROM AIR FORCE TEST BUTT SAND[a]

Sample	Particle size	Notes	Feed C_f	Concentrated fraction C_i (wt % U)	Concentrated fraction S_i (wt % of feed)	Concentrated fraction U_i (wt %)	Depleted fraction C_d (wt % U)	Depleted fraction S_d (wt % of feed)
A	30 X 100	One pass	1.3	49	2	70	0.42	98
B	100 X 200	One Pass	1.3	32	3	73	0.36	97
C	30 X 100	Multiple pass	1.3	3	38	87	0.27	62
D	30 X 100	Heated multiple pass	0.42	16	3	81	0.26	97

[a]KEY:
C = uranium concentrate
S = material split (100 x weight of fraction/weight of feed)
U = uranium split (wt % of uranium in fraction vs feed)

Subscripts
d = depleted fraction
f = feed
i = concentrated fraction

4. Chemically remove an outer layer of the sand, plus deposited alumina, usually in a basic medium, to expose DU which was trapped at the sand surface during weapons firing.

5. Dissolve the exposed DU in an acidic, oxidizing medium, and wash with water.

6. Allow undissolved Th^{234} (separated after U^{238} decay) to decay away for about two months (24-day half life).

With these treatments, the sand can be cleaned to background gamma levels, or even a bit less, when the surface material is removed. It is not clear whether the removable surface activity of natural sand from pits primarily reflects primarily recent worldwide fallout or long-time accumulation of water-carried radioactive compounds, e.g., compounds of uranium, thorium, etc. The large decontamination factors required for sand disposal require careful chemical treatments and washing.

A less expensive alternative may be to stop after Step 3 and recycle the sand to the firing pits. This sand would be dust free but would have around 1400 ppm (DU equivalent) of trapped gamma activity. The fines, about 7.5 volume percent in our sample, could be dried, possibly after pretreatment, then be safely shipped and stored. The DU scrap could be remelted and recycled.

The process appears ready to move to pilot plant operations.

According to this study, leaching Steps 1, 2, and 3 were insufficient to achieve an activity reduction allowing unrestricted onsite disposal. Implementation of these steps alone would require the partially cleansed sand to be returned to the butt instead. This report describes in detail each of the six steps required for complete sand decontamination and the degree of decontamination achieved with each step. The final conclusion of this study is also noteworthy:

> In view of the practical difficulties and costs of assuring complete decontamination of the DU-contaminated target sands, another approach, i.e., recycle of the target sands, is recommended for operations. The sand would be freed (a) of pieces of DU, (b) of readily removable uranium oxide, and (c) of dust-forming fines. However, it would not be necessary to remove uranium oxide trapped in rather unreactive films on the surfaces of the larger sand grains - they wouldsimply be returned to the target area for reuse.

SECTION IV
REVIEW OF URANIUM MINING TECHNOLOGY

As required by the scope of work statement for Phase 1, commercial technology used in the uranium mining industry was reviewed for potential application to DU/sand separations procedures at the gun test site. This review was performed and is provided in Appendix B. In addition to separations and methods used in uranium mining, Appendix B describes some of the solids handling and storage equipment used in commercial mineral handling.

Our finding is that there is little likelihood of technology carryover from the uranium mining industry to potential DU/sand separations methods appropriate for the gun test site for the following reasons:

1. At the heart of all commercial uranium mining systems is a chemical processing system based on chemical dissolution, usually with strong acid leach, followed by solvent extraction, chemical stripping, and precipitation to form U_3O_8. Although such a chemical system could theoretically be considered for use at the gun test site, it would likely be completely inappropriate; for example, operation would require a specialized crew of chemical technologists, and highly noxious acid wastes would be a by-product of the process.

2. Most other equipment used in uranium mining is selected as peripheral requirements for basically a chemical leaching system. Therefore, any direct application for the gun test facility would be largely accidental.

3. Common to all production-scale mineral treatment facilities, uranium ore handling and separations methods are optimized for large-scale, continuous operation. As such, they are characterized by numerous specialized pieces of equipment selected for continuous operation to minimize labor costs. In contrast, separations activities at the gun test site are highly intermittent and would likely optimize toward far fewer pieces of equipment with a significantly larger component of labor cost.

However, exploration of some largely developmental activities in the uranium mining industry is worthwhile. Even though the "gangue" material (i.e., the process residue) is not sand, there is some chance that some of the applications of these operations would be useful to the uranium/sand system. These processes include:

1. Large-scale wet magnetic separation of gold/uranium from waste pond sludge in South Africa. A description of a system that has magnetic separation as a heart of the process is described in Appendix B.

2. Hydroclones used to deslime and remove fine particles, enabling water recycling.

SECTION V
TARGET SAND SAMPLING AND ANALYSIS

A. SAND CONDITION AND SAMPLE LOCATIONS

Twenty samples of contaminated sand, each weighing ~400 grams were acquired from the butt in May 1988. The condition of the butt at this time may be discerned from the operations summary shown in Table 1. This table shows that the sampled sand had been in service since March 1984 and was sifted through the 1/2-inch sieve onsite on two occasions — April 1986 and May 1987. About 47,500 rounds containing 14,400 kg DU were fired into the sand in the interval from March 1984 to May 1987, of which from 50 percent to 75 percent was removed as large pieces in the two sifting operations. (The amount removed as large pieces is estimated from data provided for earlier sifting operations.) The record shows that an additional 5729 rounds containing 1719 kg of DU were test-fired following the last sifting but prior to the sampling.

Thus the condition of the sand in the butt at the time of sampling can be described as follows:

1. The roughly 260 yd^3 of sand contained from 7,200 to 10,800 kg of DU fragments smaller than 1/2 inch from the test firings between March 1984 and May 1987. This portion of the uranium is probably well mixed throughout the butt.

2. The sand also contained 1719 kg of DU debris from the subsequent firings. This portion of the DU in the butt would be concentrated in the central target zone and would consist largely of fragments greater than 1/2 inch

3. In addition, there would be a large quantity of aluminum debris from the bullet casings. As for the DU, the aluminum debris would consist of small particles from the early firings, probably uniformly distributed in the sand, and a smaller quantity from the firings following the last sifting concentrated around the central target area.

Sample locations in the butt and sample number designations are identified in Table 13. The 20 samples may be generally classified into four groups: Group I samples were drawn from near a side wall and from the butt face; Group II samples were drawn from near the target zone and from the butt face; Group III samples were drawn from near a side wall and from 3 feet interior to the butt face; and Group IV samples were drawn from the central target area and 3 feet interior. Sample weights ranged from a low of 338.1 grams (sample 13) up to 640.1 grams (sample 20).

TABLE 13. SAMPLE LOCATIONS

Sample No.	Location category[a]	Distance from wall-ground-face (ft)
1	I	3-3-0
2	I	6-3-0
3	II	9-3-0
4	II	12-1-0
5	II	12-3-0
6	I	15-6-0
7	I	3-6-0
8	I	6-6-0
9	II	9-6-0
10	II	12-6-0
11	III	6-6-3
12	IV	12-6-3
13	III	15-6-3
14	III	18-6-3
15	III	15-6-3
16	III	6-6-3
17	IV	9-6-3
18	IV	12-6-3
19	III	15-6-3
20	III	18-6-3

[a]KEY:

I	Near side wall and face.
II	Near central target and face.
III	Near side wall, 3 ft deep.
IV	Near central target, 3 ft deep.

B. SAND SIZE DISTRIBUTIONS

Sand samples from the butt and unused sand samples were classified by sieving into the nine size categories listed in Table 14.

TABLE 14. SELECTED SIZE CLASSES FOR SAND PARTICLES

ASTM Sieve No.	Size range (mm)
+10	>2.00
-10/16	2.00-1.18
-16/20	1.18-0.850
-20/30	0.850-0.600
-30/40	0.600-0.425
-40/60	0.425-0.250
-60/80	0.250-0.180
-80/200	0.180-0.075
-200	<0.075

Table 15 lists size distributions for (1) unused sand, (2) unused sand but dry-sifted for removal of coarse and fine particles, (3) wet-sifted unused sand, and (4) a composite average of the used sand in the butt at the time of sampling. [The sifted sand (Items 2 and 3), obtained from a commercial supplier near Eglin AFB, is available in bulk at a cost of about 20 percent more than unsifted sand.] The table indicates that about 83 percent of the sifted feed sand is in the -10 to +60-mesh range, about 5 percent is coarse (+10-mesh), and the balance of about 12 percent are fines (-60-mesh). Presifting the feed sand, either wet or dry, can reduce the coarse fraction to less than 1 percent, and wet presifting can reduce the fines level from 12 percent to about 3 percent. Thus, for a small additional cost, a tighter size distribution for the feed sand may be obtained.

Row 4 of Table 15 indicates the size distribution of used butt sand, averaged for the 20 acquired samples. The principal differences between unused and used sand (rows 1 and 4) are seen to be the relative amounts of coarse (+10-mesh) and extremely fine (-80-mesh) material. Use as target sand increases both the coarse and extremely fine fractions. As Table 15 shows, the coarse fraction increased from 4.7 percent to 7.1 percent of the total mass because of the addition of large bullet fragments. The extremely fine fraction (-80-mesh) increased in relative abundance from 4.8 percent to 18.3 percent of the total mass, evidently because of attrition and also production of fine-sized bullet fragments.

This situation is illustrated in Figure 8. We are envisioning the size range -10/60-mesh as normal sand. Presifted sand, as typified by Row 3 of Table 15, contains about 96 percent of its mass in this range. The figure also illustrates that the principal effect of target use on sand is the generation of coarse (+10) and fine (-60) material at the expense of the normal size range of -10/60-mesh.

C. URANIUM CONCENTRATIONS IN BUTT SAMPLES

Uranium concentrations were determined for the nine size fractions of each of the 20 samples acquired from the butt. These data are presented in Appendix C, together with the mass and uranium distributions for each sample. The analysis method involved leaching the uranium from the sand with 8 mL nitric acid followed by plasma spectroscopy of the leached solution. The accuracy of the analysis is estimated to be from ±5 percent to ±10 percent of the reported concentration.

TABLE 15. SAND SIZE DISTRIBUTIONS. UNUSED SAND AND AVERAGE OF USED SAND TARGET [MASS (%)]

Serve range	+10	10 X 16	16 X 20	20 X 30	30 X 40	40 X 60	60 X 80	80 X 200
Unused sand								
(1) Unsifted[a]	4.7	8.6	10.5	20.6	20.1	22.9	7.7	4.2
(2) Dry-sifted[b]	0.4	5.3	11.7	21.8	22.0	27.4	8.8	2.3
(3) Wet-sifted[b]	0.7	8.7	22.1	35.9	17.1	12.6	2.1	0.5
(4) Contaminated[b] sand from target (avg)	7.1	6.2	9.6	18.6	16.5	17.9	6.1	7.9

[a]Unused sand.
[b]Unused sand but sifted (dry and wet) for removal of coarse and fine fractions.

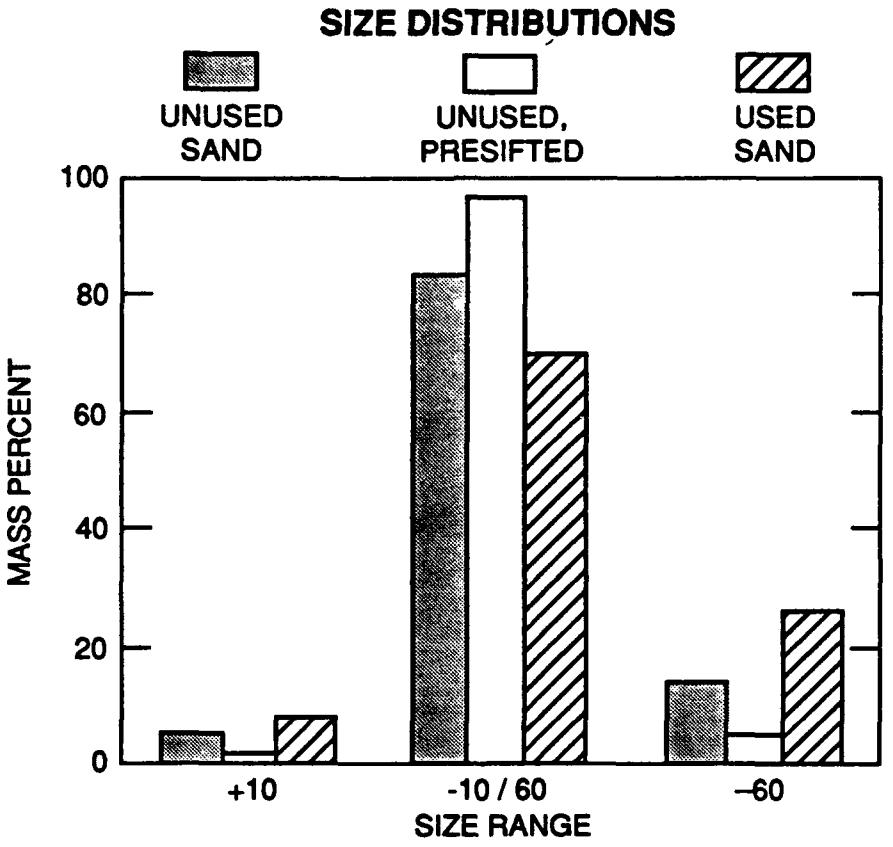

FIGURE 8. Size Distributions of Unused Sand, Unused but Presifted Sand, and Used Sand.

Concentrated nitric acid leaching dissolves metallic and oxidic uranium but not uranium silicates, if present. In one case, a lead solution containing hydrofluorine acid was used, which would dissolve uranium silicates. No difference in uranium concentration was determined for this sample within the accuracy limits of the method, indicating that no measurable amount of uranium was present as uranium silicate.

The data presented in Appendix C are grouped in Table 16 according to sample location category as defined in Table 13. Also, the size categories are reduced to the four shown to include (1) coarse sizes greater than 10-mesh, the two potential recycle ranges, (2) -10/20-mesh, (3) -20/60-mesh, and (4) the fine fraction, here defined as -60-mesh. The significance of these selected size ranges is that the coarse and fine fractions contain the highest concentrations of uranium, whereas the intermediate range, from 10- to 60-mesh, is the principal range for the feed sand. The table presents the mass percent of each fraction, its uranium concentration, and the percent of uranium in the fraction relative to the entry sample before classification.

TABLE 16. CONTAMINATED SAND SIZE AND URANIUM DISTRIBUTIONS—BY SAMPLE LOCATION AND OVERALL

Sample location category		Particle size range (ASTM mesh) +10	10 X 20	20 X 60	-60	U-conc. in sample (%)
Side, surface I	Mass, %	4.1	14.6	50.8	30.5	3.5
	U conc., %	20.7	3.1	1.4	4.9	
	U, %	24.3	13.0	20.5	42.2	
Center, surface II	Mass, %	5.2	14.0	51.3	29.6	4.2
	U conc., %	24.9	3.3	1.3	6.1	
	U, %	30.5	11.0	16.0	42.6	
Side deep III	Mass, %	15.3	16.3	52.0	16.4	13.5
	U conc., %	77.9	2.7	1.1	3.5	
	U, %	88.3	3.3	4.2	4.3	
Center, deep IV	Mass, %	5.2	18.2	56.7	19.9	4.1
	U conc., %	32.9	2.5	2.4	3.2	
	U, %	41.2	10.9	32.6	15.4	
Overall	Mass, %	7.4	15.8	52.7	24.1	6.3
	U conc., %	52.9	2.9	1.6	4.7	
	U, %	62.1	7.3	13.4	18.0	

The combined values for the 20 samples are presented in the lower portion of Table 16 and are illustrated in Figure 9. The significance here is that if these combined data are taken as representative of the butt, then about 80 percent of the uranium in the butt is contained in the coarse (+10-mesh) and fines (-60-mesh) fractions. These fractions would contain about 30 percent of the butt mass, in this case. However, since much of the coarse and fine mass is made up of material in the feed sand, use of more tightly sized sand, such as described in Section V.B and Figure 8, could significantly reduce this amount of material. As an approximation, the data presented in Section V.B indicate that the mass of the coarse plus fines fractions may be reduced to from 15 to 20 percent of the total through use of presifted sand.

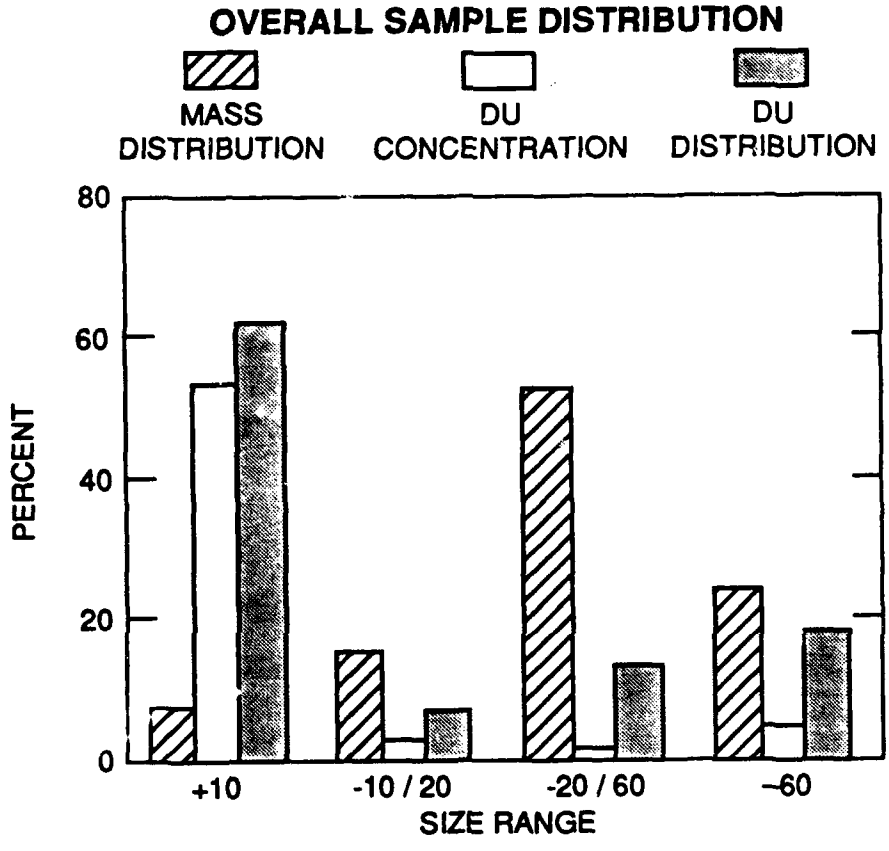

FIGURE 9. Overall Size and Uranium Distributions for the 20 Samples

SECTION VI
ALTERNATIVE URANIUM-SAND SEPARATIONS OPTIONS

A. SCREENING (WET AND DRY)

Since the DU fragments have been shown to concentrate primarily in sizes larger than the average diameter of normal sand, screening for removal of the larger fragments is a logical first step in the sand cleaning operation. In addition, most solids separations devices function optimally on feed consisting of relatively uniformly sized particles. For this additional reason, screening of the target sand into a reasonable number of size classes would be a required initial step in a decontamination procedure.

The classification of screening operations and the range of separations that can be attained with various screens are given in Table 17 (Reference 5).

Although a screen may look like a simple piece of equipment, it is based on some complex design features. The important factors in the design and construction of screens are as follows (Reference 6, p. 215):

1. The main function of a sizing screen is to separate undersize particles from a feed, whatever the range of particle sizes in the feed, by letting undersize particles pass through the apertures in the screen. This separation must achieve a stated efficiency at a given feed rate.

2. The construction must be sufficiently robust for the designed function, and the flow design should be such as to minimize wear and tear. Also, mechanically, the machine must provide a suitable mode of solids transportation so as to allow separation to be achieved most effectively.

3. Maintenance costs and power consumption should be as low as possible.

4. The screen should not cause excessive spillage or degradation of the material during its operation.

Details on screening systems are outlined in Reference 7, Section 3E, Vol. 1. One of the important points to consider is that screening and screening selection is more of an art than a science. This is because there are a dozen or more different types of screens from which to choose and many different manufacturers with conflicting claims to efficiency and uniqueness.

TABLE 17. TYPES OF SCREENING OPERATIONS (REFERENCE 5)

Operation and description	Type of screen commonly employed
1) Scalping: the removing of a small amount of oversize from a feed which is predominantly fines.	Coarse (grizzly)
2) Separation (coarse): Making a size separation at 4-mesh and larger.	Vibrating screen, horizontal or inclined
3) Separation (fine): Making a size separation smaller than 4-mesh and larger than 48-mesh.	Vibrating screen, horizontal or inclined; high-speed low-amplitude vibrating screens; sifter screens; static sieves; centrifugal screens
4) Separation (ultrafine): Making a size separation smaller than 48-mesh.	High-speed low-amplitude vibrating screen; sifter screens; static sieves; centrifugal screen
5) Dewatering: Removal of free water from a solids-water mixture. Generally, limited to 4-mesh and above.	Horizontal vibrating screen; inclined vibrating screens (about 10°); centrifugal screen
6) Trash removal: Removal of extraneous foreign matter from a process material.	Vibrating screen, horizontal or inclined; sifter screens; static sieves; centrifugal screen
7) Other applications: Desliming, conveying, media recovery, and concentration.	Vibrating screens, inclined and horizontal; oscillating screens; centrifugal screens

Generally under such conditions, operation experience on handling similar material plays an important role in determining merits of different units. To arrive at a properly designed screen installation, two additional items must be considered: (1) a body of data from the designer and (2) the data on the screen and the manufacturer's knowledge. The information which the selection needs falls into the following groupings: (1) the characteristics of the material being processed, (2) the process flow sheet, (3) the type of screening operation involved, (4) the physical constraints of the plant, and (5) the operator's equipment preferences. All these areas play a role in the successful installation of a screening system.

Screening machines may be divided into five main classes: grizzlies, revolving screens, shaking screens, vibrating screens, and oscillating screens (Reference 8). Grizzlies are used primarily for scalping at 0.05 meter (2 inch) and coarser, while revolving screens and shaking screens are generally used for separations above 0.013 meter (1/2 inch). Vibrating screens cover this coarse range and also down into the fine meshes. Oscillating screens are confined in general to the finer meshes below 4-mesh. Further details are given in Reference 8, p. 21-B.

In attempting to pick a screening machine, it should be emphasized that generalized formulae and charts will give only an approximation because of the many variables that may affect performance. Laboratory and field tests provide the most dependable criteria for screen design.

Many screening variables can readily be changed in the field. Examples are given below.

1. Method of Feed

The feed must be spread evenly over the full width of the screen for maximum efficiency.

2. Screening Surfaces

The most efficient screening results when a series of single-deck screens is used. This is true because lower decks of multiple-deck screens are not fed so that their entire area is used and because each separation requires a different combination of angle, speed, and amplitude of vibration for maximum performance.

3. Angle of Slope

The optimum slope of inclined vibrating screens is that which handles the greatest volume of oversize and still removes the available undersizes required by the standards of the particular operation.

To separate a material into coarse and fine fractions, the bed thickness must be limited so that vibration can stratify the load and allow fines to work their way to the screen surface and pass through the opening. Increased slope increases the rate of travel, and at a given rate it reduces the bed thickness.

4. Direction of Rotation

In circle-throw screens, somewhat greater efficiency can be obtained by counterflow rotation, that is, having the material move down the screen against the rotation. Screens rotating with the flow of material will handle greater tonnage and operate at a lower angle.

Dust control measures may be required wherein enough moisture is added to enable screening but to stop the dust from becoming a hazard. However, since handling of contaminated water may also be a problem, it is desirable to minimize this water usage.

Thus, an optimal design with a minimum usage of water may be necessary. The feed may change characteristics as rounds are fired into the bunker; thus, a satisfactory design of a screening system must be able to respond to the following changes:

a. feed size distribution,

b. amount of debris, and

c. different moisture contents.

B. WET SEPARATIONS METHODS

Solid-solid separation in water media is discussed in handbooks such as the SME Mineral Processing Handbook (Reference 7) and in texts such as Solids-Liquid Separation (Reference 6). We shall discuss only those processes which have already shown promise or those which have potential for application at the gun test site.

1. Gravity and Centrifugal Concentration

As mentioned in Sections III and V, uranium may not exist in pure form and may additionally be oxidized or splattered on the sand particles. In either case, the effective specific gravity may be between 18 and 2.65. Characterization of contaminated sand samples included determination of particle density distributions from selected, sized fractions. These characterizations provide a sounder basis for assessing the degree of uranium separation that may be expected from wet classifiers.

There are two basic types of wet classification: pool and elutriation. In pool classification, a suspension is fed into and out of a pool of some kind at such a rate that only part of them, the faster settling part, has time to settle out. The remainder overflows as fines or the less dense particles. In elutriation classification, the feed suspension is introduced into or above one or more columns or pockets through which water is rising at a controlled velocity. Coarse or heavy particles subside through the pockets and are removed through spigots. Those which settle slower than the rising velocity in any column or pocket are prevented from subsiding (assuming no secondary flow complications) and so must overflow. These elutriaters or sizers are capable of sharper separation than pool classifiers (Reference 7).

The principle of these separators is illustrated in Figures 10 and 11. The main advantage of such systems is their inherent simplicity. Since the system depends on terminal velocity, to achieve maximum separation caused by density difference, the particles need to be closely sized and larger than ~50 μm.

Separation of uranium/sand can also be obtained using a hydroclone, which is depicted in Figure 12. The hydroclone depends on external power for its operation, supplied, in this case, by a continuous flow centrifugal pump. Feed velocity head and pressure head are converted to both angular and linear velocity, creating a cyclone effect, where the angular velocity increases as the feed liquid moves from the outside wall of the cyclone toward the axis of rotation.

As the angular velocity increases, the centrifugal forces cause the separation of particles by size or specific gravity. Although the common mechanical hydrocyclone designs are relatively simple, there have been many unusual and relatively complicated designs developed over the years, each attempting to solve what was then perceived to be a particular operating problem. The number of these designs is great, and the improvements of the basic operations are nebulous (Reference 7).

Details of design methodology have been outlined in References 6 and 7. As with the screens and classifiers, some simple scoping experiments may be advantageous to determine the actual separation parameters.

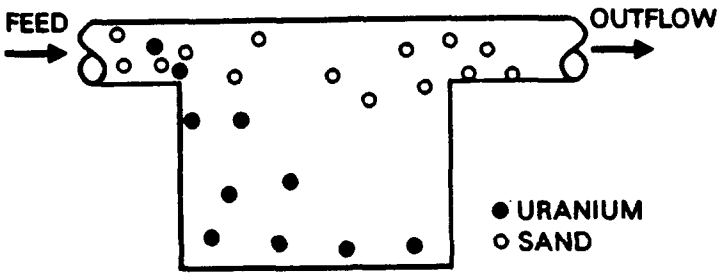

FIGURE 10. Separation of DU/Sand by Pool Classifier.

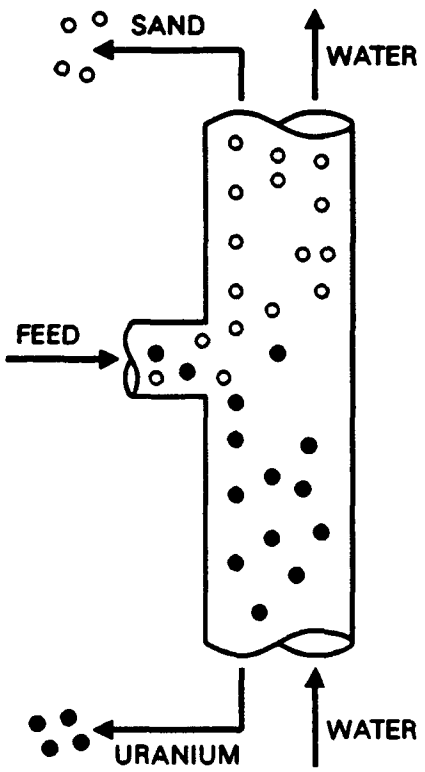

FIGURE 11. Separation of DU/Sand by a Water Elutriating Column.

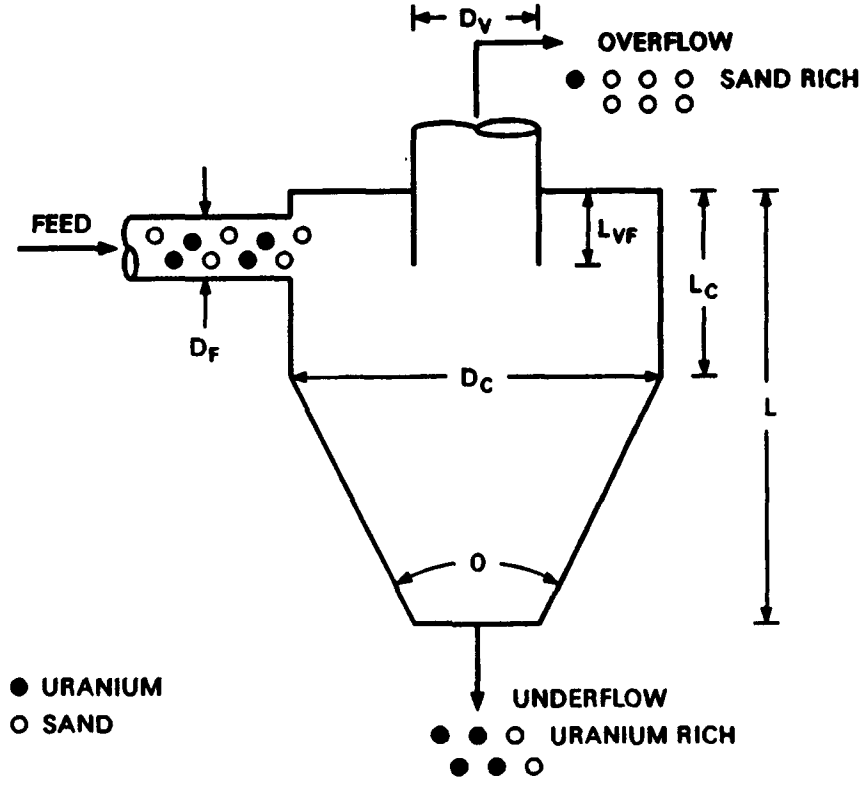

FIGURE 12. Principle of Hydroclone for DU/Sand Separation.

2. Gravity Concentration Devices Used in the Mineral Industries

The range of applicability of various concentration devices used in the mineral industry is given as a function of particle size in Table 18. Gravity concentration devices are available for particles ranging from 10 μm to 10 cm or greater. These devices can be extremely efficient in separating relatively well-liberated, coarse particles; but both their capacity and efficiency decrease as the particles become smaller. When any substantial amount of fine particles is present (below ~100 μm or 150-mesh), flotation or magnetic separation techniques are preferred where applicable.

TABLE 18. APPLICATION RANGE OF VARIOUS CONCENTRATION DEVICES

Device	Particle size range (cm)
Picking and sorting	>1
Coarse jigs	>0.1
Placer jigs	10^{-2} to 1
Heavy media static bath	>1
Heavy media hydroclone	0.1 to 10
Water cyclone	10^{-2} to 1
Shaking table	10^{-2} to 0.1
Spiral	10^{-2} to 0.1
Flowing film concentrator	10^{-3} to 0.1
Air table	<0.1 to >1
Electrostatic separation	10^{-2} to 0.1
Flotation	$<10^{-3}$ to $>10^{-2}$

In this section we shall discuss (1) jigs, (2) spirals, and (3) shaking tables. These devices have been tested with uranium/sand mixtures, as discussed in Section III.

a. Jigs

In jigging, a mixture of particles supported on a perforated plate or screen in a layer or "bed" with depth many times the thickness of the largest particle is subjected to alternating rising and falling flow of fluid with the objective of causing all the particles of high specific gravity to travel to the bottom of the bed while the particles of lower specific gravity collect at the top of the bed. Jigging is the ideal preconcentration or sorting process, being relatively cheap in construction, operation, and maintenance and relatively unaffected by the change in feed particle size distribution and concentrations. Traditionally, jig operation required experienced operators and jigging was a skill. However, with the recent developments in control and instrumentation technology, a less experienced operator can now run a jig.

The separating mechanisms in a jig are typically (1) hindered settling, (2) pulsed-flow acceleration, and (3) dense-bed penetration and percolation.

The liquid pulse in the jig, in its ideal form, is a modulated sine wave. For particles of equivalent settling velocities but different specific gravities, it has been calculated (Reference 7) that only a few strokes are necessary to attain efficient separation. For the larger particles, there is a part of the stroke where their movement is stopped by the supporting screen, and the only motion possible is that of percolation or trickling of fine particles downward through the spaces.

This effect may be used to separate fine metallic particles of uranium, which could be drawn down through a bed of coarse sand particles by the descending water.

However, in any jig application, the size distribution and the specific gravity of the particles of metal will result in a unique situation requiring optimization of each of the jig actions.

All modern jigs are of the fixed-bed type in which the liquid pulse passes up and down through the jig bed, which is retained on a stationary screen.

Jigs are best suited to handling coarser materials. They also use large amounts of water, which may be a disadvantage. As discussed in Section III.B, the success of the jig to separate uranium from sand has been modest.

b. Spirals

The most popular form of the spiral is the Humphreys spiral. It consists of a curved channel arranged in the form of a spiral having a 13-1/2-inch pitch with provision for concentrate withdrawal through ports along the inner part of the spiral. Wash water is supplied in an auxiliary trough from which it can be deflected into the main pulp stream.

Spirals have a fairly low installation cost and low operating and maintenance costs (Reference 7, p. 4-48). The best results are achieved on large-tonnage operations since in small installations (one to four units) economies are seldom seen over competitive devices. This feature may be of disadvantage to the uranium/sand separation process in which no large volumes are to be processed continuously.

The feed slurry and wash water flow rates are the most important variables. They vary between 15 and 20 gal/min for the feed and 3 and 15 gal/min for the wash water. When

either volume is too low, it causes a sluggish flow and sand bar formation, resulting in reduction of both concentrate and capacity. On the other hand, excessive volumes cause the high-specific-gravity mineral to be swept wide of the upper port, resulting in sand bar formation in the lower turns.

The feed size is usually between 14- and 200-mesh, which is a wide range and quite suitable for uranium/sand operations.

Spirals have been used extensively for recovery of heavy minerals in beach sands. Initial tests with uranium/sand as discussed in Section III.C have shown excellent uranium recoveries, with only small quantities of sand in the concentrate.

c. Tabling

Tables are used for processing large flow rates of coal and lesser amounts of barite, beach sands, chrome, glass sand, garnet, iron, manganese, mica, phosphate, potash, tantalum, tin, titanium, tungsten, and zircon (Reference 7, p. 4-32). In addition, they have found application in the nonore uses such as recovery of metal from foundry sands and recovery of machine shop metal grindings and turnings from abrasives. For this reason, this technology appears attractive for uranium/sand separations.

The separation achieved on a wet concentration table is a result of numerous factors acting simultaneously on the table feed. These include film-flowing concentration, hindred settling, trickling of fine particles through voids, and acceleration caused by asymmetrical movement of the table. The table also has a set of riffles to separate the coarser and less dense particles into a particular channeled outflow path. Separation by tabling is achieved by both size and specific gravity of the particles. In many operations, water elutriators are combined with tabling; so particles of the same terminal velocity are fed into the tabling separators in which particles of higher density are separated from the less dense. The largest size input is about 3/8 inch, and the lower limit is about 200-mesh. This presents a wide range of sizes for separation. Also, a difference of at least 1.0 specific gravity units between the two particle systems is necessary for rapid and efficient separation, provided all other factors are equal.

As discussed in Sect. III.C, a separation test using tabling was conducted on uranium/sand, and it was found that this method did not achieve good separation.

3. Other Methods

a. Magnetic

Magnetic methods in wet media separation are relatively new in the mineral separations area and still are considered to be in the R&D stage of development. There are principally two methods of wet magnetic separations:

- high gradient and
- open gradient using superconductors.

Most of the work in this area has been done in the mining field. The results have shown that good separation can be achieved with both high gradient and open gradient with superconductors. The basic advantage magnetic separation has over gravity and centrifugal concentrators is that it can handle relatively fine particle sizes. However, relatively narrow size ranges are needed for proper operation. In addition, for the high gradient separator, there has been a problem in keeping the matrix, which provides the high field, clean of debris. Also, the disadvantage of the superconductor is that it has, as yet, not been proven under field conditions.

b. Flotation

Flotation in the recovery of uranium has been applied successfully in the mining area for separation of fines. The disadvantage in application of the technique to the present process is the requirement of addition of chemicals and careful monitoring of the pH levels and relative densities.

c. Leaching

Leaching of uranium/sand mixtures presents a method by which extremely high recovery fractions of uranium can be obtained. Details of such processes are discussed in Appendix B. The disadvantage of such process is (1) addition of chemical contaminants, (2) high cost, and (3) controls and maintenance requirements.

C. DRY METHODS

In dry separation methods, the conveying fluid would most likely be air. However, there may be some risk of dust fire from uranium fines, in which case an inert gas may be required, which would add cost to the separation systems. Three dry separations methods that may achieve satisfactory separation of uranium from sand are magnetic, electrostatic, and dry classifiers.

1. Magnetic

There are two dry methods for separating uranium/sand by magnetic means. These are (a) high gradient and (b) open gradient, possibly with a superconductor. The high gradient dry method is similar in principle to the wet process in which a ferromagnetic mesh has to be used to generate the high gradient field. However, the problem of keeping the high gradient matrix from plugging remains as a design challenge since there is no water to flush the uranium particles out. These must be removed by vibration and/or blowing with air or other gas.

The literature provides a study of uranium/ore separation by dry methods using high gradient magnetic field (see Appendix B). The efficiency of separation is slightly better than that achieved in wet high gradient separation.

There is some R&D work on uranium separation from mining wastes using open gradient magnetic separation in a dry medium. This has been discussed in Section IV, and the results show a good separation efficiency.

To fully evaluate the applicability of dry magnetic separation methods, we need to perform bench-scale tests with the uranium/sand from the test sites. There are factors that must be evaluated for this process, for example, verification of the excellent separations achieved on a laboratory scale with a bench-scale unit and some assessment regarding its suitability for field operation.

2. Electrostatic

This method of separation is based on differential attraction or repulsion of charged particles under the influence of an electric field (Reference 8). Applying an electrostatic charge to the particles is one method for electrostatic particle separation. Various techniques can be used for charging.

The amount of charge stored on a particle is limited by the maximum achievable charge density and the surface area of the particle. Because of balance of initial and electrical forces, there is an upper size of about 1.5 mm beyond which electrostatic separation cannot be achieved. There is also a smaller size limit of about 200-mesh for which electrostatic separation can be achieved.

Electrostatic methods are widely used in the processing of ores with mineral concentrates. This method has been used to separate uranium/sand in a preliminary study, as discussed in Section III.C. To adopt this method, some R&D has to be done on evaluating the control parameters. In addition, there is a potential danger for sparks to cause a fire with uranium dust.

In terms of simplicity of operation and robustness, this method does have a disadvantage for the process, which requires a rough and easy-to-handle process under field conditions.

3. Dry Classifiers

Air classifiers quite often form an important part of refuse processing plants in which separations of valuable components is required. The separation occurs mainly because of the difference in terminal velocities between the components. However, inefficiencies are introduced because of particle mixing effects that are caused by the secondary flows. The principles underlying the design of air classifiers are discussed in Reference 10.

According to the literature, there are no data present in the dry classification of uranium/sand. However, several commercial dry classifiers of various types are available, including fluidized bed or swirling flow, which could be applied provided sufficient differences exist in terminal settling velocity. The success of the wet spiral classifier reported in Reference 2 indicates that terminal settling velocity differences are sufficient for good separation and therefore that air classifiers could be similarly effective. At the same time, they may offer some operational simplicity relative to the wet classifier since no water storage and pumping system is required. However, the dust control situation must be carefully evaluated.

D. RANKING OF URANIUM/SAND SEPARATION SYSTEMS (OTHER THAN SCREENING)

In this section, we evaluate the separation system for uranium/sand other than the necessary initial wet or dry screening step. Since the initial screening step will reject particles greater than about +10-mesh, where bullet fragments appear to concentrate, and also fines less than about -30- to -60-mesh, further sand treatment options would deal with the intermediate range, that is, sizes between approximately -1C to +30 or -10 to +60-mesh.

To aid evaluation of each process, we have split the important selection factors into six categories. For each category, we assign a value in which the highest is 10 and the lowest is 1.

1. Simplicity
   - Amount of peripheral equipment required
   - Adaptable to intermittent use
   - Number of trained personnel for operation
   - Control systems
   - Monitoring

2. Ruggedness
   - Adaptability to field conditions
   - Maintainability

3. R&D required
   - Need to develop the process further
   - Amount of basic information required

4. Cost and commercial availability

5. Safety
   - Fire hazard
   - Health hazard

6. Separation factor
   - Effectiveness of separation of uranium from sand for this process

A value of 10 is assigned to an attribute of a separations device that appears to be particularly suitable. For example, the "ruggedness" of wet classifiers, hydroclones, jigs, spirals, and shaking tables is judged very suitable for the intended service relative to the other wet separations devices. The "performance parameter," which is intended to be a measure of overall suitability of the device, is estimated as the sum of the six individual parameters times their weighting factor. Operational safety and degree of separation have been assigned the highest factor of 2.

Naturally, this attempt at objectivity is nonetheless composed of a series of subjective evaluations. Estimates of the relative separations factors have been obtained largely from the scoping test data reported by the K D Engineering Co. (Reference 2).

As Table 19 shows, wet separations devices based on particle density or terminal settling velocity as a group grade highest in this evaluation format. As a group, these devices are simple, rugged, require only a modest degree of testing, and should present no operational safety hazard. Their chief drawbacks are (1) the requirement for a water supply and storage system and (2) some uncertainty on the degree of separation. K D Engineering tests, however, showed excellent separations results for spiral classifiers and somewhat poorer results for jigs and shaking tables. They did not test wet classifiers or hydroclones. Of this preferred group, spiral classifiers are rated somewhat higher than linear classifiers and hydroclones; however, the differences are probably smaller than the degree of uncertainty in the rating.

Wet magnetic devices are rated somewhat lower than the group of wet separations devices based on density largely because of their higher complexity, which may render them less suitable for onsite conditions. In addition, the high gradient types have high cost, and few units have been sold. As noted earlier (Section III), separations factors for the open gradient magnetic devices show a great deal of uncertainty.

Leaching, which is not suited for the intended service, is rated the lowest of the wet methods. Although leaching methods can be devised to capture essentially all of the uranium (Reference 4), they would entail an operation akin to that described in Appendix B for the uranium mining industry, which would, in addition, generate large volumes of liquid contaminated wastes.

As the table shows, dry separation methods are rated somewhat lower than equivalent wet methods because of lower operational safety due to dust generation. However, if suitable dust control measures, such as providing for a ventilated building, are of reasonable cost, then dry separators may prove to be competitive with the best of the wet devices. For example, the trade-off between the wet spiral and the dry classifier, which may have roughly equivalent degrees of separation, is increased costs for dust control versus increased cost for water supply and storage for the wet system.

In summary, an improved sand decontamination system would require size classification by sieving as an initial step, followed by a second device (if cost-effective) to improve the degree of uranium removal from the recycle sand. For this second device, spiral classifiers are rated with the highest overall performance parameter. If wet separations devices prove less attractive, because of water handling complexities, then the open gradient magnetic separator and the common air classifier would be the leading dry methods for the second separations step.

TABLE 19. COMPARISON OF URANIUM/SAND SEPARATIONS DEVICES (EXCLUSIVE OF SCREENING)

Separations device	Simplicity	Ruggedness	R&D	Cost/ commercial availability	Safety	Separations factor	Overall performance parameter
Weighting factors	(1)	(1)		(1)	(1)	(2)	(2)
Wet methodes							
Classifiers	6	10		5	8	10	6	61
Hydroclones	6	10		5	10	10	6	63
Jigs	5	10		6	10	10	5	61
Spirals	5	10		7	9	10	8	67
Shaking tables	5	5		7	10	10	5	62
High gradient magnetic	4	5		5	1	9	8	49
Open gradient magnetic	3	4		3	8	9	1-9	38-45
Leaching	2	3		7	1	6	10	45
Dry methods							
High gradient magnetic	7	5		5	1	7	8	48
Open gradient magnetic	6	4		4	8	7	1-9	38-54
Electrostatic	6	5		4	8	4	7	47
Dry classifiers	6	10		6	10	5	6	54

SECTION VII
RECOMMENDED IMPROVED SAND/URANIUM SEPARATION SYSTEM

A. OBJECTIVE

The objective of an improved uranium/sand separation system is to lower overall operating costs, particularly the cost of contaminated sand disposal. This could be done by methods that increase the usable sand lifetime, which, in turn, would decrease the disposal costs of contaminated sand per average operating year. If the useful life of the sand in the butt can be extended indefinitely, uranium disposal costs would be limited to the relatively small volume of projectile fragments produced. The high cost of disposing of large quantities of contaminated sand would be avoided completely until use of the test site is terminated. There may be a reasonable chance of achieving this result. As a minimum, the improved separations procedures described below should provide for significantly longer sand life than currently experienced by improved uranium removal techniques from the coarse-sized sand and by provision for removal of the fines.

It should be mentioned that a goal of essentially complete uranium removal enabling onsite disposal of contaminated sand is probably not cost-effective because of the low contamination level required. This would be extremely difficult to accomplish because of the intimate manner in which some of the uranium is mixed with the sand particles and would very likely require chemical leaching methods such as those described in Reference 4.

B. EVALUATION SUMMARY

1. Nature of DU in the Sand

The sampling and analysis work reported in Section V and Appendix C, together with the data and the operations reports regarding onsite sifting all point toward the following distribution of DU in the contaminated sand:[7]

a. Perhaps 50 to 75 percent of the uranium contamination exists as bullet fragments that are clearly larger than sand particles. Therefore, up to about 75 percent of the DU may be removed by capture of approximately +10-mesh-sized particles.

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[7]H. C. Harris, Eglin Air Force Base, personal communication, 1988.

b. A secondary concentration of uranium is found as (or associated with) particles clearly smaller than the range or normal sand, that is, sizes less than about 60-mesh. This includes ~18 percent of the DU. These fines should, at any rate, be removed from target sand for operational reasons.

c. Approximately 20 percent of the uranium exists as (or associated with) particle sizes that correspond to that of normal sand, that is, from approximately -10- to +60-mesh. Preliminary indications are that uranium in this size range is amenable to separation to some degree, based on particle density (or terminal settling velocity), magnetic susceptibility, or electrostatic means.

d. The following forms of uranium in the -10/+60-mesh range are known to exist: (a) metallic fragments,(b) oxidized uranium, both UO_3 and UO_2 and (c) formerly molten metal splattered on sand particles. In addition, the following forms of uranium in sand particles may exist: (d) uranium oxides associated with sand grains and (e) uranium silicates dissolved in sand.

2. Improved Sand Properties

Since the uranium contaminant in sand has been shown to concentrate in the larger sizes (predominantly +10 but also down to +20-mesh) and as well in the fines (-60-mesh approximately), use of feed sand composed exclusively of particles in the intermediate range of -10/+60-mesh (approximately) may significantly aid the separations process. This would also serve to reduce disposal costs by minimizing the quantity of contaminated sand. If sand exclusively of this size range were used, it would be clear that all particles outside this range are either uranium fragments or otherwise the result of testing operations and hence would be discarded. Currently, about 6 percent of the as-received sand consists of larger sizes (+10-mesh), and about 6 percent may be classed as fines (less than 60-mesh). We have identified a presized sand product available for delivery to Eglin of approximately these size characteristics for a cost of $12 per cubic yard, relative to about $10 per cubic yard for unsized sand. The size distribution of this sand is shown in Figure 8 and Table 15, labelled as "unused, pre-sifted sand."

Since a significant fraction of the uranium is associated with particles in the size range -10/+20-mesh, an even superior sand product would be one with a somewhat tighter size range, -20/+60-mesh. Sand with this tight size range would exclude all except about 10 percent of the uranium contamination

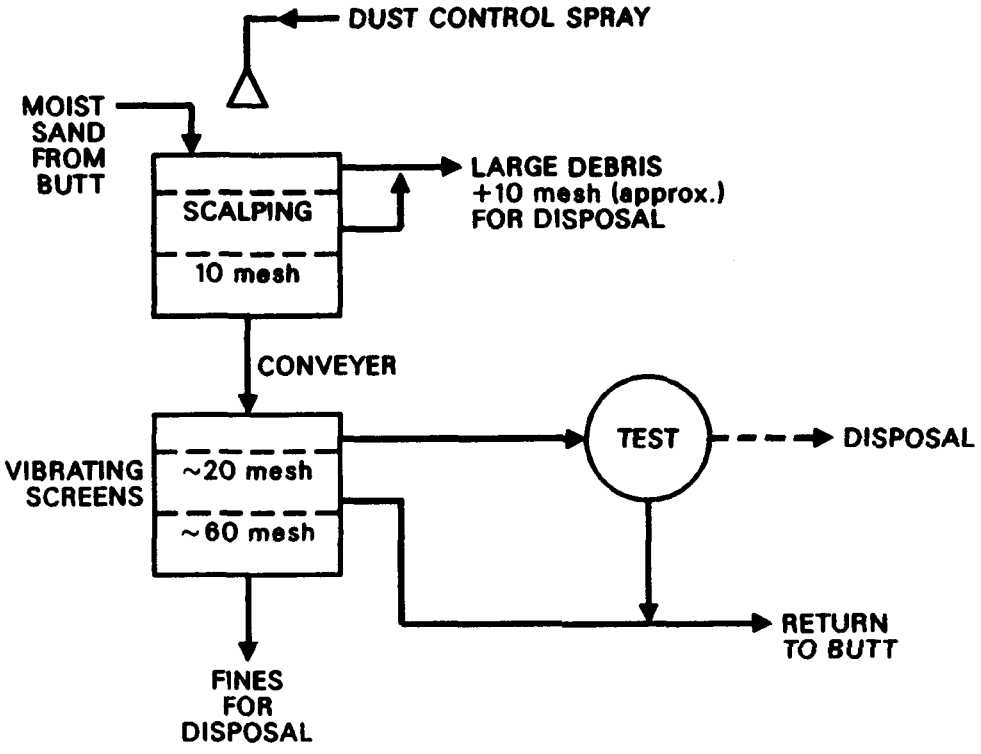


FIGURE 13. Option 1, Improved Screening Procedure.

below +10-mesh size. Hence, a considerable degree of separation would be permitted by sieving alone. However, it is not currently known if acquisition or onsite preparation of -20/+60 sand is cost-effective.

3. Preferred Separations Options

The logical initial sand treatment step is one involving size classification by sieving in order to (1) capture from 50 to 75 percent of the uranium sized or associated with sand particles above +10-mesh, (2) separate and discard the fines (about -60-mesh), which are proportionately high in uranium and which, in addition, tend to clog the filters in the target building, and (3) obtain sized fractions of target sand as required to improve the performance of the subsequent (if any) separations step.

The evaluations presented in Section VI indicate that a further treatment of the contaminated sand beyond improved sieving, if proven to be cost-effective, would best be accomplished by a spiral classifier. However, it was also noted that operation of a wet separation system may be more complex than currently accounted for. Wet system complexity involves provisions required for the water system, including pumps, storage vessels, dewatering devices, and perhaps some special treatment for decontamination by removal of fines. If wet separations prove to be unwieldy, evaluations have shown that the preferred dry separation procedure is the air classifier or an open gradient magnetic device, provided the high separations factors observed by Hoegler can be achieved on a commercial prototype.[8]

C. IMPROVED SAND SEPARATIONS OPTIONS

Improved sand separations methods can significantly increase the usable lifetime of the butt sand and reduce the volume of contaminated material required for disposal. The simplest improved system (Option 1), shown in Figure 13, involves upgraded screening techniques. In Option 1, moist sand from the butt is fed to a scalping screen (as in the current operation), which experience shows removes from 50 to 75 percent of uranium debris in the sand. The same unit would contain coarse mesh screen (~10-mesh), and coarse, +10-mesh particles would be combined with

[8]J. M. Hoegler, "Magnetic Separability of Uranium from Sand," unpublished ORNL report to Eglin AFB, 1987.

the larger sizes for disposal. According to data from Reference 2, the +10-mesh fraction should remove about 50 percent of the uranium that passed through the scalping screen. Therefore, from 75 percent to about 82 percent of the fed uranium may be removed in the large debris fraction, which would consist largely of uranium (and aluminum) pieces.

The performance of the scalping plus 10-mesh screen unit may be enhanced if presized sand were used in the butt. For example, if sand initially fed to the butt were screened for removal of +10 particles, essentially all of the large debris reject from the scalping plus 10-mesh unit would consist of bullet fragments, thereby minimizing the mass of the disposed material.

The principal function of the vibrating screen assembly in Option 1, fed possibly by a conveyor from the first unit, is the removal of fines. Fines may be defined as particles less than about 60-mesh, although a final selection of this cutoff size must be optimized later. Defining fines to begin at a somewhat larger size, for example, 40-mesh, would speed up and simplify screening removal but may add significantly to the mass of this disposal stream.

Fines removal, as indicated earlier, would increase the usable sand lifetime by reducing the tendency for clogging of the HEPA filters in the target building. In addition, uranium contaminant has been found to concentrate in the fines. Sampling analyses reported in Section V and Appendix C indicate that about 18 percent of the DU is associated with the -60-mesh sizes, which is consistent with Reference 2, which reports that about 15 percent of the uranium that passed the scalping screen existed in -65-mesh-sized fractions. Adding this to the 75 percent to 82 percent estimated removal in the scalping plus 10-mesh step yields an estimated total uranium removal by the screening operations in Option 1 to be from 78 percent to 89 percent of the fed uranium.

Fines removal may be improved by use of presized sand. Removal of -60-mesh sizes from sand fed to the butt would signify that essentially all fines removed by screening would consist of material produced by the bullet testing process.

In Option 2, shown in Figure 14, an additional removal step is performed on the -10/+60 size fraction from the vibrating screen prior to returning the sand to the butt. Since most of the uranium is likely to exist in the -10/+20 portion of this fraction, the second stage separation step is shown in Option 2 to process only this size fraction. The feed to the second stage separator, which would be selected following bench-scale tests conducted in Phase 2, would include only about 11 percent to 22 percent of the uranium originally fed to the scalping screen. Whether or not this second-stage separations step is cost-effective would be determined by evaluation conducted in Phase 3 using test data developed in Phase 2.

The second-stage separations step could use either a wet or dry separator. Current assessments outlined in Section VI lead to a preference for wet separations because of enhanced safety; however, a full assessment of costs entailed in the use of wet systems, particularly the manner in dealing with water possibly contaminated in excess of 40 pCi/mL, has not yet been determined.

A wet, second-stage separations flow sheet, shown in Figure 15, indicates a requirement for at least one pump, two dewatering screens, a water storage unit, and some provision, probably in the water storage unit, for fines removal by settling. The greatest risk in the selection of a water separations system lies in the possibility (perhaps small) in water contamination by carbonate or an acidic source which would cause a degree of uranium solubility in excess of 40 pCi/mL.

The best options for the wet separations unit include, as Section VI evaluations indicate, the spiral classifier, jigging, and the linear classifier, with a current preference for the spiral.

A dry separations option for the second-stage separations step is shown in Figure 16, using a commercially available open-gradient magnetic device. The system is notably simpler than classifiers based on terminal settling velocity, which require dewatering (or air separation and filtration for dry classifiers). The principal uncertainty regarding its use relates to the degree of separation achievable with a commercially available device.

1. Extension of Usage Times of the Air Filter System in the Target Building

The existing system for removal of dust in the bunker is by means of withdrawal of air at the rate of about 5000 $feet^3$/min by a compressor through a prefilter and a HEPA absolute filter, which is required for handling radioactive dust. Details of this assembly are discussed in Section II. When this filter system gets clogged, the filters must be replaced and the

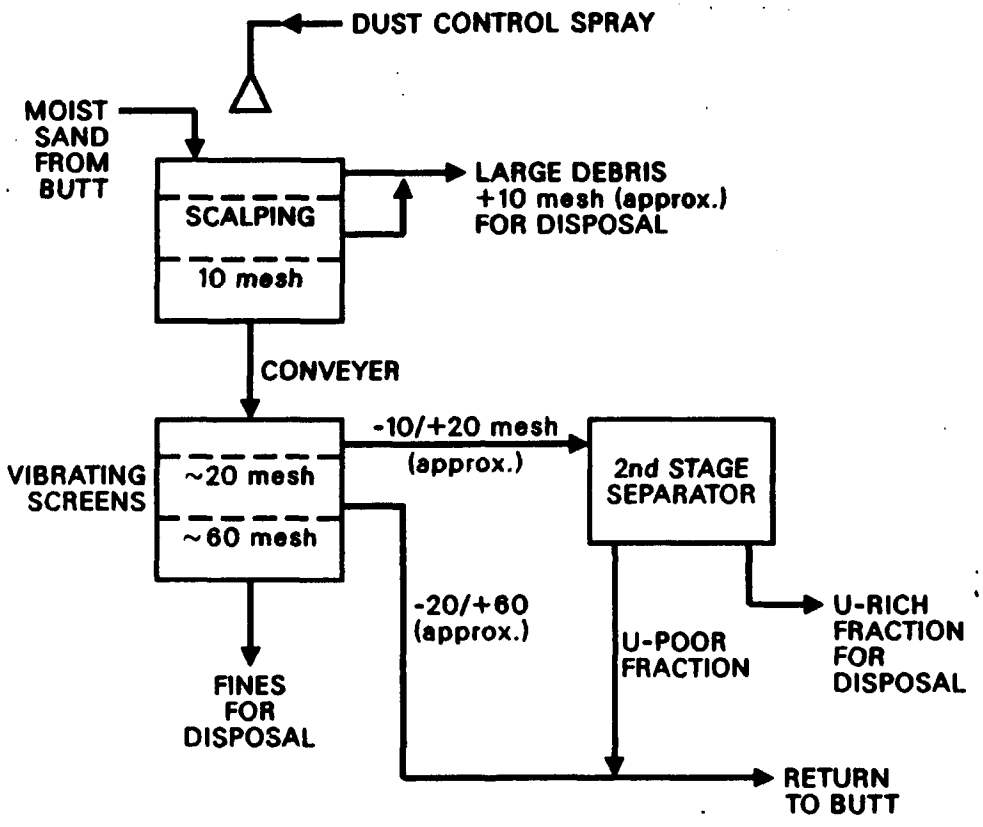
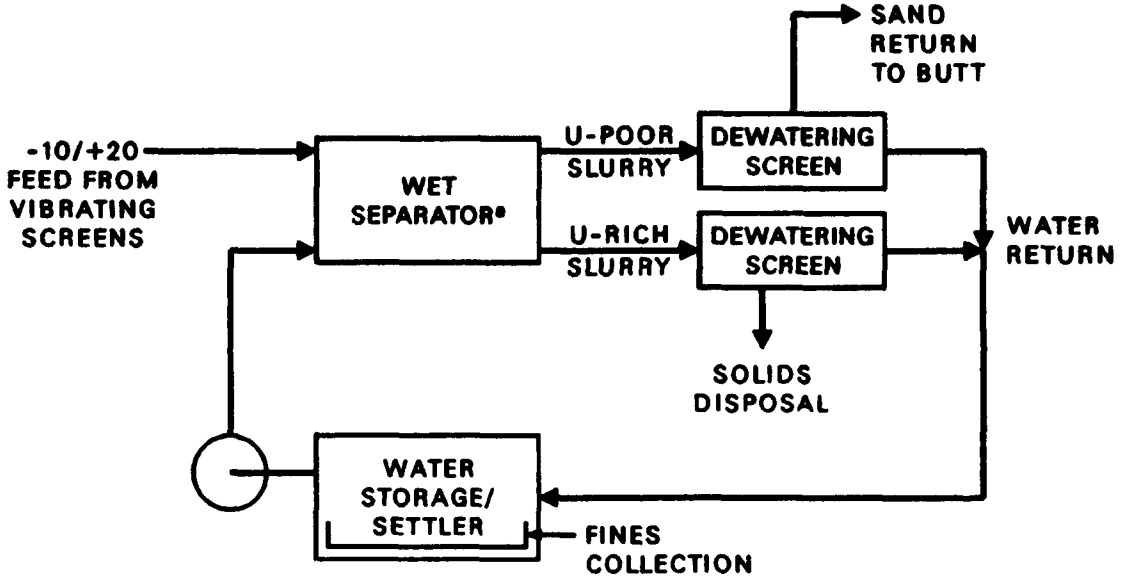


FIGURE 14. Option 2, Improved Screening Plus Second-Stage Separation.



[a]SPIRAL CLASSIFIER, JIG, OR LINEAR CLASSIFIER

FIGURE 15. Wet Separation Option for Second-Stage Separator.

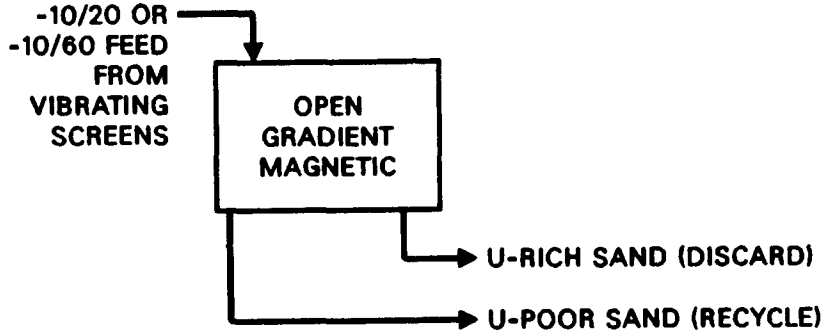


FIGURE 16. Dry, Open Gradient Magnetic Separator for Second-Stage Option.

fines in the bunker taken out. It may be possible to extend the useful life of the filter and make it more useful in removing the fines by having a semicontinuous dust removal system before the existing filter system, which may consist of a series of cyclones or baghouse filters with automated removal of dust into a dust hopper. By this means, it may be possible to remove greater than 99 percent of the dust before it gets into the HEPA filter. This may result in extension in life for the filter system and thus contribute to the projected useful life of the sand.

SECTION VIII
ALTERNATIVE CATCHMENT MEDIA

A. INTRODUCTION

1. Criteria for Selection of Alternative Media

The following criteria are deemed appropriate for consideration of alternative catchment media for the Eglin gun test facility:

a. Easy and complete DU recovery.

b. Improved catchment operation; that is, the cost and time involved in separating DU from sand, as required in the current system, should not be replaced by a different but roughly equivalent effort.

c. Safe operation; principally, no flammable or toxic media can be considered.

d. Robust design; systems requiring complex or high-speed mechanical devices would be inappropriate for basically a gun test facility because of the requirement for specialized personnel.

2. Alternative Catchment Options

It appears that only two types of alternative catchment media hold any chance of satisfying the required criteria:

Option 1 - Water or density-enhanced water solutions.
Option 2 - Ice of various possible forms.

Other options were considered but rejected, based on the above criteria. For example, plastic foams such as polystyrene foam particles are attractive from a number of considerations but must be rejected because of their flammability.

In addition, some members of the class of halogenated alkanes and alkenes were considered as suggested by their application in heavy media separations equipment. Some of these materials show promise at first look by virtue of their high density, which would reduce the required catchment length by a factor equal to the density ratio relative to water. (For example, tetrabromoethane has a density of 2.9.) Further, it may be possible to choose from this class of compounds a mixture which is solid at test temperature but which could be molten by modest temperature elevation to effect the DU separation, a highly advantageous feature. (As an example, tetrabromoethylene

has comparable density to tetrabromoethane and melts at 56°C.) Unfortunately, as a class, these liquids are slightly unstable in the presence of moisture, resulting in liberating the toxic gases HBr and Br_2, especially Br_2 at temperatures near the boiling point. Equally serious is their inherent modest toxicity and the potential for reaction with uranium as result of bullet-to-bullet impacts that create high localized temperatures. These reactions may form various uranium bromides, possibly some UBr_4 vapor, and liberate heat. Therefore, halogenated alkanes and alkenes were dropped from consideration.

3. New Facility Versus Adapting Existing Facility

Conversion of the current building for use with a superior stopping medium would be ideal if it were possible. However, discussions in following sections indicate that adaptation of the existing catchment building to a water medium would not be feasible because of excessive wall pressure. Adaptation to ice is likewise not recommended for several reasons presented in Section VIII.B.

A speculative concept for a horizontally oriented catchment using water that may replace the existing catchment building but use the existing gun test facility is discussed in Section VIII.C.

It is evident that target buildings using liquid media are most naturally suited to a vertical alignment, principally because of the natural means for liquid containment during and after test firing. A possible additional and potentially major benefit of the vertical orientation for rapid, sequential firings (for brevity, termed a salvo) would be a more rapid collapse of the vapor wake of each bullet because of the increase in static pressure with depth. Therefore, a shorter catchment may suffice for a salvo compared to an equivalent for a horizontal alignment. However, a vertically oriented catchment would require a completely new test facility, that is, a new gun building and vertical remounting of the gun.

B. CONSIDERATION OF ICE CATCHMENTS

1. System Description

The potential advantage of ice as a catchment medium lies in the possibility of combining the beneficial features of sand and water media. That is, ice pieces of several possible types may, like sand, bear a load under impact and so shield the walls of the target building from the force of the bullet impacts. In contrast, bullet impacts into water would transit pressure directly to the wall. However, as with water, DU may be easily separated by simply melting the ice.

Because it is a solid, load-bearing medium, ice may be worthwhile considering as a replacement for sand in the existing catchment building. If shown to be feasible, the existing catchment building may be adapted with some fairly extensive modifications, including:[9]

a. The ice-maker would be installed on the building roof, requiring support for its weight and provision for maintenance of the unit.

b. A front wall would need to be fabricated, including a guard shield, to protect the ice-maker from stray bullets.

c. A water sealant would be required for the building interior.

d. A drain equipped with a sieve for collecting the DU must be installed.

e. Very possibly, the building length would need to be extended because of the diminished stopping power of ice relative to sand.

In addition to these building modifications, a supporting water storage and handling system would need to be installed, including a water pool of ~16,000 feet^3 capacity for water storage, a pump/filter unit for emptying the catchment following a test firing, and feed pumps from the storage pool and to the refrigeration unit.

Operation of the ice-maker itself appears to present a reasonable set of time and cost parameters, for example, use of a commercially available 300-ton, IGC model manufactured by the Turbo Refrigeration Company. Operational parameters are listed in Table 20 and are based on preliminary catalog data for this model, which is the largest unit manufactured by this company. The required fill time is marginal at 28 hours; the electric cost per filling is estimated at $1200. Sheets of ice 1/4 inch thick are formed by this unit, which would likely require tamping to achieve a satisfactory density.

2. Conclusions Regarding Ice Catchments

Although ice catchments offer a means for easy and complete DU recovery, examination of the required system reveals that cumbersome operational procedures would be required.

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[9]The following evaluation indicates that adaptation of the current facility to ice is not recommended.

Specialized personnel would be required for the operation and maintenance of the refrigeration unit. Long periods of nonoperation would be detrimental to the unit, adding to maintenance costs.

TABLE 20. ICE CATCHMENT OPERATIONAL PARAMETERS

Catchment parameters	
Volume of catchment	479 m^3 (16.9 X 10^3 ft^3)
Mass of ice (30 % voids)	3.23 X 10^5 kg (7.1 X 10^5 lb_m)
Refrigeration parameters	
Unit size	300 ton
Performance factor (estimate)	1 kW(e)/ton
Cost of unit (estimate)	$290,000
Operational parameters	
Electric energy per filling	3.1 X 10^7 kW•s
Electric cost per filling	$1200 @ 14¢/kW/h
Required fill time	28 h

The chief attraction of an ice catchment would be the possible adaptation of the current building. However, this would require extensive building revisions of a degree which possibly surpasses the investment of a substantially improved sand separation system. Moreover, the cratering characteristics of various forms of ice particles are not known; therefore, it is not clear if lengthening of the catchment building would be required. Therefore, consideration of adapting the current facility to an ice catchment medium cannot be recommended.

Ice catchments should, however, be considered for a possible future facility. Along with water, which may be the only other reasonable alternative medium, it offers a facile procedure for complete DU recovery. Moreover, it fits better to a horizontal orientation than water and may require a less sturdy building because of the load-absorbing properties of solid ice particles.

On the negative side in comparison with water, a substantial investment in refrigeration equipment would be required, with the attendant costs of specialized personnel for operation and maintenance. Additionally, cratering characteristics of various ice particle forms would need to be determined.

C. CONSIDERATION OF A WATER MEDIUM

1. General Considerations

The chief advantage of water lies in the prospect for complete and easy DU recovery. Moreover, one can envision a relatively simple system requiring no specialized operations since only simple supporting equipments, such as a transfer pumps and valves, would be required. The chief disadvantages of using water lie in its inherent properties as a liquid:

a. There is an uncertainty in the response of either a closed (no free surface) or open (with a major free surface) water pool to a rapid sequence of nearly colinear bullets. The concern is that the size and rate of collapse of the vapor wakes would be such that a rapid bullet sequence would require excessive stopping length.

b. In contrast to a solid as a stopping medium, significant pressures generated by bullet impacts would be transmitted to the container walls. Either steel or prestressed concrete containers designed for sharp, repetitive internal pressure loadings would be required.

c. The water medium is most naturally suited to a vertical gun test orientation for both containment and vapor cavity collapse considerations. However, a vertical orientation would require a new test building, an extensive vertical working distance either above or below ground, and a vertical gun mount.

The stopping power of a catchment medium for high-velocity bullets depends primarily on its density and its strength. On both counts, water is poorer than sand. However, density enhancement by massive addition of a heavy salt appears to be a feasible method for obtaining a significant degree of density increase. A number of highly soluble heavy salts such as calcium bromide exist which should be relatively inexpensive and obtainable on a bulk scale. The approximate densities of saturated calcium bromide solutions are listed in Table 21, where it is seen that solution densities in excess of 2.0 g/cm^3 may be realized. As the table shows, use of calcium iodide could result in an approximately threefold density increase over plain water at possibly a significantly higher cost. Operation with concentrated $CaBr_2$ or CaI_2 solution should present no more hazard than use of concentrated sodium chloride.

TABLE 21. APPROXIMATE DENSITIES OF SATURATED WATER SOLUTIONS

	$CaBr_2$ (g/cm^3)	CaI_2 (g/cm^3)
0°	2.25	2.82
10°	2.32	2.94
20°	2.43	3.09
40°	?	3.43
60°	?	3.85

2. Penetration of Single Bullets in Liquids

The stopping force on a bullet is related to its rate of momentum loss by

$$M\frac{dv}{dt}=\frac{1}{2}\rho AC_D v^2 \qquad (1)$$

where
M = bullet mass,
v = bullet velocity,
ρ = liquid density,
A = bullet area projected on plane perpendicular to velocity,
C_D = drag coefficient.

Taking M, A, and C_D as constant leads to the following simple result:

$$\frac{v(x)}{v_o}=\exp(-Kx), \qquad (2)$$

where $K = \rho AC_D/2M$. In actuality, C_D varies with velocity and in a major way with the directional aspect of the bullet with respect to its velocity vector. In addition, the impact of the bullet may alter the parameters M and A, which, in turn, also effect C_D. Therefore, Equation (2) is useful only for a scoping estimation of required stopping length.

We note from Equation (2) that the principal medium property affecting velocity attenuation is its density. Liquid viscosity has a much lower effect, entering only by lowering the projectile Reynolds number, which consequently increases C_D. However, a viscosity increase of many orders of magnitude would be required before its effect were significant.

The orientation of the bullet axis relative to its velocity has a major effect on C_D. For example, the value of C_D for a cylinder moving colinear to its axis (arrow aspect) is -0.4 at Re = 106 and about 1.5 for a crosswise aspect at Re = 106. (The incident Reynolds number for the present case is about 3.4×10^7, assuming pure water at 1 cp viscosity and an incident velocity of 1340 m/s.) Data for C_D at these high Reynolds numbers are not readily available, but extrapolating from a standard source (Reference 11) leads to an estimate for C_D of 0.8 for the right cylinder in an arrow aspect and 1.5 for crosswise velocity at the incident Reynolds number. Therefore, the departure of bullet orientation with respect to an initial, arrow-like aspect would reduce the penetration depth. Some single projectile penetration depths are listed in Table 22 and are based on the following parameters:

$M = 0.3$ kg,
$v_o = 1340$ m/s,
$v(\text{final}) = 10$ m/s.

TABLE 22. ESTIMATED PENETRATION DEPTHS OF SINGLE PROJECTILES IN WATER

	Projectile penetration to 10 m/s (m)	
	Standard water	Density-enhanced water (ρ = 2 g/cm^3)
Arrow aspect	7.3	3.7
Cross-flow aspect	0.95	0.48

3. Salvo Characteristics

The term "salvo" here signifies a rapid firing of nearly colinear bullets consecutively from seven barrels. A firing rate of either 4200 rounds per minute (RPM) or 2100 RPM may be selected, the higher rate corresponding to 10 rounds per second from each of the seven barrels. To date, the maximum single test duration has been about 3 seconds and 210 rounds.

Figures 17 to 19 illustrate a typical firing pattern for a 150-round salvo[10]. Figure 17 shows the total scatter for all seven barrels as measured 1000 inches from the muzzle. Since the actual catchment distance is roughly 1500 inches, scatter at the catchment should be roughly 50 percent greater than illustrated in these figures. At a 100-inch range, 100 percent

[10]H. C. Harris, Eglin Air Force Base, personal communication, 1988.

of the bullets are enclosed within a 14.4-inch-diam circle centered at x, y coordinates (1.84, 5.80) inches relative to coordinate center. Figures 18 and 19, for barrels 1 and 2, respectively, illustrate that the firing center for each barrel differs, typically by several inches at 1000 inch downrange.

The mean target coordinates for each barrel and for all seven barrels are summarized in Table 23 for this illustrative case. The distance between the mean target coordinates of successive barrels ranges from 1.9 to 5.6 inch at this range and the time lapse between successive bullets is 14.3 ms at the 4200-RPM firing rate. One firing cycle is completed in 100 ms.

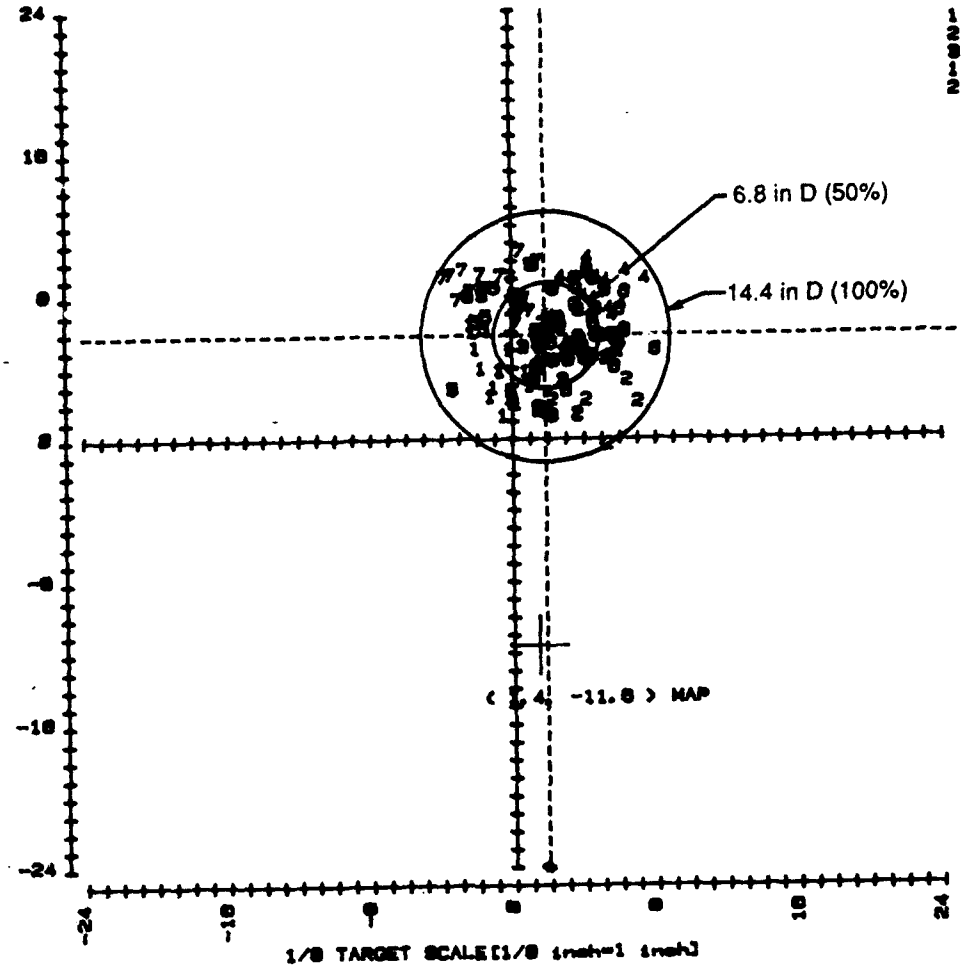
The difficulty in application of water catchments lies in the nature of its response to a salvo such as that described. In principle, a complete description of catchment and trajectory characteristics could be obtained using a "cratering" code such as the HULL code, provided a sequence is assigned to the bullets in the salvo. However, no data on bullet sequence are available, and adaptation and execution of HULL code runs to such a case involving a bullet sequence would require some degree of reprogramming. However, some tentative indications of water response to impacts from the typical salvo data can be formed. These include:

a. A water catchment designed to collapse the vapor wake in <14 ms would require a stopping length for the salvo that is no greater than for the individual bullet, that is, from about 7 meters for ordinary water down to ~3.5 meters for density-enhanced water. The speed of vapor wake collapse is therefore a critical parameter for the feasibility of water catchments.

b. If the speed of vapor wake collapse significantly exceeds 14 ms, some sort of major vapor crater growth would progressively develop by a complex interaction with successive bullets. In the (improbable) limit of extremely slow collapse of large-diameter vapor wakes, a stopping length equal to the number of salvo bullets times the individual bullet-stopping length would be required, a clearly impractical situation.

MISSION NUMBER: 7230

AUTOMATIC TARGET SCORING SYSTEM 99.9



DATE: ---------- 9 MARCH BURST NUMBER: 6535

TOTAL ATS SCORES: 150 ; TOTAL ATS 99.9 SCORES: 5

MEAN IMPACT POINT: [X]= 1.84 ; [Y]= 5.80

CIRCLE MIL DIAMETER AT 1000 INCHES FROM WEAPON:

100% = 7.2, 90% = 5.0, 80% = 4.6, 70% = 4.2

60% = 3.8, 50% = 3.4, 40% = 2.8, 30% = 2.4

20% = 2.0, 10% = 1.4

BORESIGHT MAP TO BURST MIP: X= 0.4, Y= 17.4

1.4 DEG/ 8.7 MIL

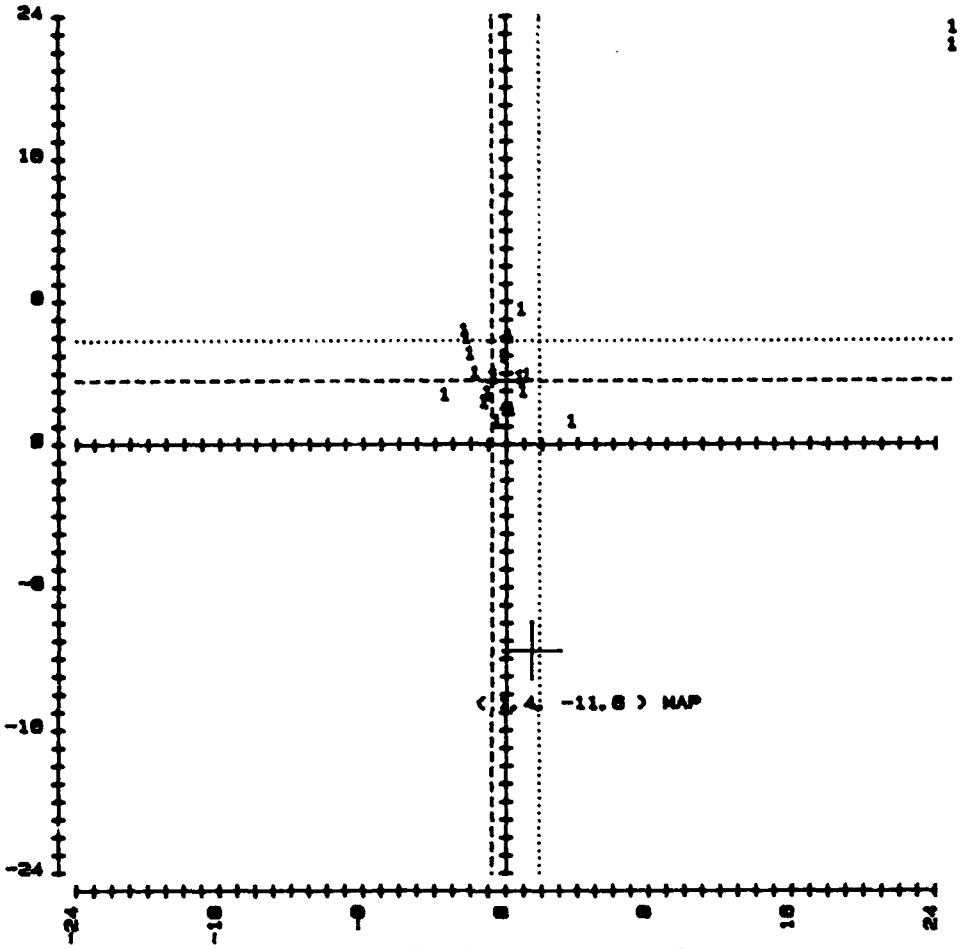
BARREL MIP: ..... BURST MIP: ----------

ATS PLOT FOR ALL BARRELS

FIGURE 17. Typical Firing Pattern - 7 Barrels.

MISSION NUMBER: 7230

AUTOMATIC TARGET SCORING SYSTEM 99.9



1/8 TARGET SCALE[1/8 inch=1 inch]

DATE: ---------- 8 MARCH BURST NUMBER: 8535

TOTAL ATS SCORES: 150 ; TOTAL ATS 99.9 SCORES: 2

MEAN IMPACT POINT: [X]= -0.80 ; [Y]= 3.58

CIRCLE MIL DIAMETER AT 1000 INCHES FROM WEAPON:

100% = 4.8, 90% = 3.2, 80% = 2.8, 70% = 2.4

60% = 2.0, 50% = 1.6, 40% = 1.6, 30% = 1.4

20% = 1.2, 10% = 0.4

BORESIGHT MAP TO BURST MIP: X=-2.2, Y= 15.1

351.7 DEG/ 7.8 MIL

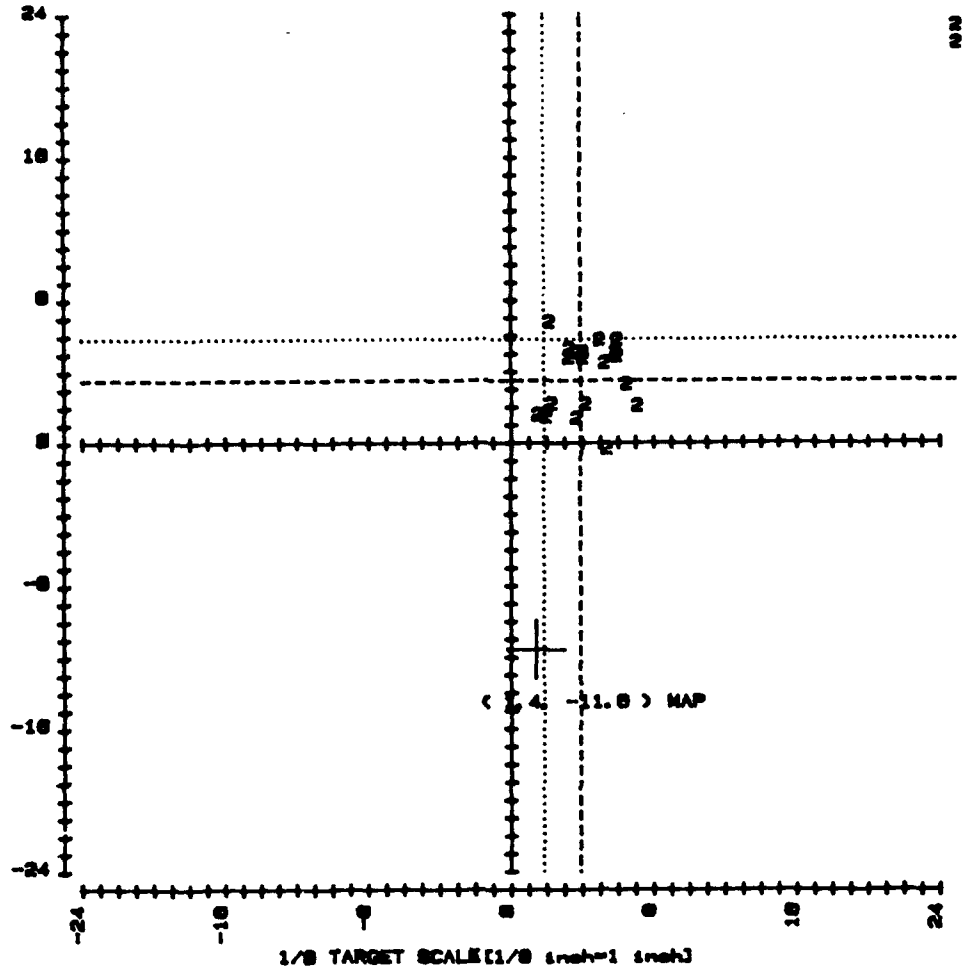
BARREL MIP: ..... BURST MIP: ----------

ATS PLOT FOR BARREL 1

FIGURE 18. Firing Pattern - Barrel 1.

MISSION NUMBER: 7230

AUTOMATIC TARGET SCORING SYSTEM 99.9



1/8 TARGET SCALE[1/8 inch=1 inch]

DATE: ---------- 8 MARCH BURST NUMBER: 8535

TOTAL ATS SCORES: 150 ; TOTAL ATS 99.9 SCORES: 2

MEAN IMPACT POINT: [X]= 3.90 ; [Y]= 3.49

CIRCLE MIL DIAMETER AT 1000 INCHES FROM WEAPON:

100% = 4.2, 90% = 3.6, 80% = 3.2, 70% = 2.8

60% = 2.2, 50% = 2.0, 40% = 2.0, 30% = 1.8

20% = 1.4, 10% = 1.2

BORESIGHT MAP TO BURST MIP: X= 2.5, Y= 15.1

0.4 DEG/ 7.8 MIL

BARREL MIP: ..... BURST MIP: ----------

ATS PLOT FOR BARREL 2

FIGURE 19. Firing Pattern - Barrel 2.

TABLE 23. TYPICAL MEAN COORDINATES FOR EACH BARREL AND DISTANCES BETWEEN SUCCESSIVE MEAN COORDINATES, AT 1000-IN. RANGE

	Mean coordinates (in.)		Distance between successive mean coordinates (in.)	Time lapse from initial bullet (ms)
	$\bar{x}$	$\bar{y}$		
1	-0.80	3.58	4.70	0
2	3.90	3.49	2.24	14.3
3	2.01	4.70	2.36	28.6
4	0.19	6.20	4.39	42.9
5	4.24	7.89	1.89	57.2
6	4.30	6.02	5.62	71.5
7	-0.90	8.15	4.57	85.8
All barrels	1.84	5.80		

c. The vapor wake diameter for individual bullets (d_w) and the degree of noncolinearity of successive bullets (Δx_c) would affect the nature of the developed vapor wake when collapse times exceed 14 ms. A following bullet will strike some water and thereby have its trajectory altered provided that

$$\Delta x_c > \frac{1}{2}(d_w - d_b) \tag{3}$$

where d_b is the bullet diameter of about 1 inch Since x_c generally ranges from about 2 to 5 inch (Table 23), following bullets will strike some water provided vapor wakes are less than from 5 to 11 inch in diameter.

4. Speed of Vapor Wake Collapse

a. Horizontal Catchment with Free Surface

The collapse time of a horizontal vapor wake at depth Z in a water pool with a major free surface may be roughly approximated by assuming that the principal effect of the incident bullet kinetic energy is to elevate water above the entry depth Z to a height DZ; that is,

$$Mg\Delta Z = KE_b \tag{4}$$

where

M = water mass above Z, ~ ρ g W Z ΔX,
ρ = water density,
Z = wake depth,
W = width of pool,
ΔX = stopping distance of bullet,
ΔZ = water elevation resulting from bullet,
KE_b = bullet incident kinetic energy.

The collapse time, Δt_c, would then be approximated by the time required for free fall from height, ΔZ; that is,

$$\Delta t_c = \sqrt{\frac{2\Delta Z}{g}} \tag{5}$$

This is essentially an order of magnitude estimate of collapse time. The point, however, is that long collapse times may be expected when bullet penetrations force free surface motion on vapor wake generation. Closing the wake, in such case, requires bulk motion of some of the pool, usually by action of a gravity body force. Substituting terms from Equation (4) into the above leads to the following expression for collapse time of the vapor wake:

$$\Delta t_c = \frac{1}{g}\sqrt{\frac{2KE_b}{\rho WZ\Delta x}} \tag{6}$$

Some approximate collapse times are listed in Table 24 for various bullet entry depths, assuming a typical pool width of 5 m and an individual bullet-stopping length of 5 m. As the table shows, collapse times for wakes in horizontal pools are predicted to be far too long to avoid excessive vapor cavity growth for any reasonably sized pool.

TABLE 24. APPROXIMATE VAPOR WAKE COLLAPSE TIMES AT VARIOUS BULLET ENTRY DEPTHS

Assumed depth of wake (m)	Collapse time (ms)
1	460
10	140
20	100
100	46
1000	14

Assumed parameters:
Pool width = 5 m
Stopping length = 5 m
$KE_b = 2.7 \times 10^5$ J
$\rho = 1000$ kg/m^3

b. Vapor Wake Collapse Rate in Closed Catchments

A closed catchment is here defined as one with no free surface. In such case, the bullet impact causes water compression in the process of forming the vapor wake. The rebound of the water to its normal density provides the means for speedy collapse of the vapor wake. The rate of collapse may be estimated by drawing an analogy with the time constant of a spring.

Writing the restoring force of a spring as

$$F = -\frac{k\Delta x}{L} \tag{7}$$

where
k = spring constant, N
Δx = spring displacement, m
L = spring length, m,

leads to a time constant for the spring of

$$T = 2\pi\sqrt{\frac{mL}{k}} \tag{8}$$

where m = mass on the spring.

A cylindrical water catchment of radius, R, containing compressed water and a vapor wake presents an analogous 2-D situation. Drawing the analogy with the spring, the developed restoring pressure would be

$$\Delta P = \frac{1}{\beta}\frac{\Delta V}{V} \tag{9}$$

where $1/\beta$, the reciprocal of the water compressibility, plays a role analogous to the spring constant. The time constant for water rebound from a bullet impact in a closed, water catchment may therefore be written

$$T = \pi \frac{\rho R^2}{1/\beta} \tag{10}$$

where one-half the complete cycle has been taken as the collapse time. Since b for water has a value of ~4.6 X 10-5 atm-1, Equation (10) predicts a cavity collapse time of 10.1 m for a 5-m-radius catchment and a 4-ms collapse time for one of 2-m radius.

An alternate estimate of the collapse time in a closed catchment may be obtained by assuming that vapor wake collapse occurs when the resulting pressure wave returns from a wall rebound. The resulting collapse time is then

$$T = \frac{2R}{C} \tag{11}$$

where R is the catchment radius and c the velocity of sound. For water, c = 1447 m/s. Thus, Equation (11) predicts T = 7 ms for a 5-m-radius catchment.

In either estimate, the collapse time appears to be shorter than the 14-ms duration between successive bullets, which is encouraging. Therefore, a closed water catchment would be acceptably small. However, a practical means for designing a nearly closed water catchment that at the same time is sufficiently open to allow bullet entries (for the salvo) would need to be conceived.

5. Water Pressures Resulting from Bullet Impacts

Water pressures resulting from individual and sequential bullet impacts would result from a complex interplay of shock wave motion generated at the bullet leading edge as well

as a possible generalized pressure increase resulting from kinetic energy absorption in the water as a whole from the salvo. Reasonably accurate determination requires sophisticated modeling. At this stage, only rough approximations of water pressure elevation are presented.

Bullets may create localized shocks even though nominal speeds are less than the sonic velocity. For such cases, a local shock pressure may be estimated from

$$\Delta P_{shock} = \rho v c \qquad (12)$$

where

ρ = water density, 1000 kg/m3,
c = sonic velocity, 1447 m/s,
v = bullet velocity, 1340 m/s.

A localized shock pressure of 1.94 X 10^9 N/m^2 (2.91 X 10^5 psi) would thereby result. The pressure would attenuate as the shock front grows from the bullet to the vessel wall, by approximately the ratio, R_{wake}/R_{vessel}. Assuming an initial shock cylinder of 0.02 meter, approximately the bullet radius, and a vessel diameter of 5 meter results in an attenuation factor of 250 or a wall pressure of 7.76 X 10^6 N/m^2 (1160 psi). Thus, to withstand a rapid fire sequence, the catchment wall would need to withstand a rapid sequence of sharp pressures on the order of 1200 psi.

In addition to the rapid sequence shock impacts, a closed catchment would experience a general pressure elevation because of the absorption of bullet kinetic energies. For example, for a 3-second duration test firing 210 bullets (the maximum salvo to date), the total absorbed kinetic energy would be ~5.78 X 10^7 J. Distributed over a 5-meter radius catchment of 10-meter depth would result in a pressure rise of

$$\Delta P_{salvo} = \frac{210 X KE_b}{V_{catchment}} = \frac{5.78 X 10^7 J}{785 m^3}$$

= 7.4 X 10^4 N/m^2 (11 psi) .

Thus, this rather large-diameter catchment would experience a small, generalized pressure rise of ~11 psi.

6. Adaptation of the Current Catchment Building to Water

The subject adaptation is thought to be not feasible because of the following:

a. high, repetitive shock pressures at the wall of the order of 1000 psi,

b. excessive vapor wake "cratering" of the water pool due to movement of the free surface, which would therefore require stopping lengths much in excess of the current length of the target building.

7. Code Simulation of Water Catchments

Several computer runs of the HULL code were performed to verify some of the estimates of water catchment response discussed above. HULL is a complex system of codes intended principally for describing solids behavior under intense load (Reference 12). The code contains viscoplastic and viscoelastic dynamic models, as well as sophisticated thermodynamics capability for determing material states at high temperatures and pressures. Primary use is for predicting behavior of projectile impacts with armor or other solid objects. The HULL code was set up and run for the water catchment cases by W. R. Hendrich of the Solids Mechanics Section in ORNL's Engineering Technology Division.

In principle, water catchment response to a series of bullet impacts may be completely modeled using HULL. In practice, however, excessive CPU times would be required unless reprogramming can allow significant speedup for this specific case. For example, a real-time span of at least 42 ms would be required for a duration that includes three projectiles, 14 ms apart. In contrast, two runs were executed using simplifying assumptions (one projectile, no projectile deformation or direction change, cylindrical symmetry); each run required ~5 h CPU time for 1.6 ms real time. Nevertheless, some of the objectives of the HULL code runs were met despite the limited real-time duration.

a. Objectives of HULL Code Runs

Using simplifying assumptions (described below) for scoping calculations, the following objectives were set:

(1) Verification of the approximate velocity decay equation for cylindrical bullets in water [Equation (2)].

(2) Verification of the pressure pulse at the wall, estimated to be 7.76 MPa (1160 psi) using Equation (12).

(3) Determination of the diameter of the vapor wake of the bullet under both "open" and "closed" catchment assumptions.

(4) Determination of the collapse rate of the vapor wake, under both "open" and "closed" catchment assumptions.

b. Case Assumptions

Two cases were run which differed only in whether or not the water volume did or did not possess a free surface. (These are termed "open" and "closed" catchments, respectively). For both, the water volume was assumed to be a 2-m-diam cylinder of infinite length within an unyielding container. An open front face was taken to be the free surface for the "open" case. For the "closed" case, the cylinder was assumed to be completely enclosed, with the bullet already internal at time zero. Other parameters common to both cases were (1) single projectile, (2) projectile mass = 300 g of DU arranged as 1.50-cm-diam cylinder by 9.0 cm long, and (3) initial velocity = 1340 m/s.

c. HULL Code Results

Figures 20-22 shows three plates indicating the pressure pattern in the water for the "open" catchment situation at times 0.7, 1.0, and 1.595 ms following bullet entry. Figure 23 and 24 shows two similar pressure patterns for a "closed" situation at times 0.7 and 1.049 ms. For each case, the bullet is progressing in the direction at x = 0, with the blue area[11] behind indicating the wake. Unfortunately, the pressure zones between 5 and 100 MPa (725 to 14,500 psia) are shown in close shades of red, these color distinctions will not be apparent in a black-and white reproduction of the subject figures, which are difficult to distinguish. However, one may draw a few tentative conclusions from examination of these plates and other output material not shown.

(1) The velocity decay of the bullet is approximately that predicted by the approximation, Equation (2), which is to be expected since no aspect alteration was permitted in these runs.

(2) A maximum wake radius for the "open" catchment case of ~20 cm (7.9 inch) is seen at t = 1.595 ms, extending up to about 40 cm along the bullet path, followed by a region where a wake radius of ~8 cm (3.1 inch) is seen. No great difference is seen for the "closed" catchment, although wake diamaters appear to be somewhat less at corresponding times.

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[11]These color distinctions will not be apparent in a black-and-white reproduction of the subject figures.

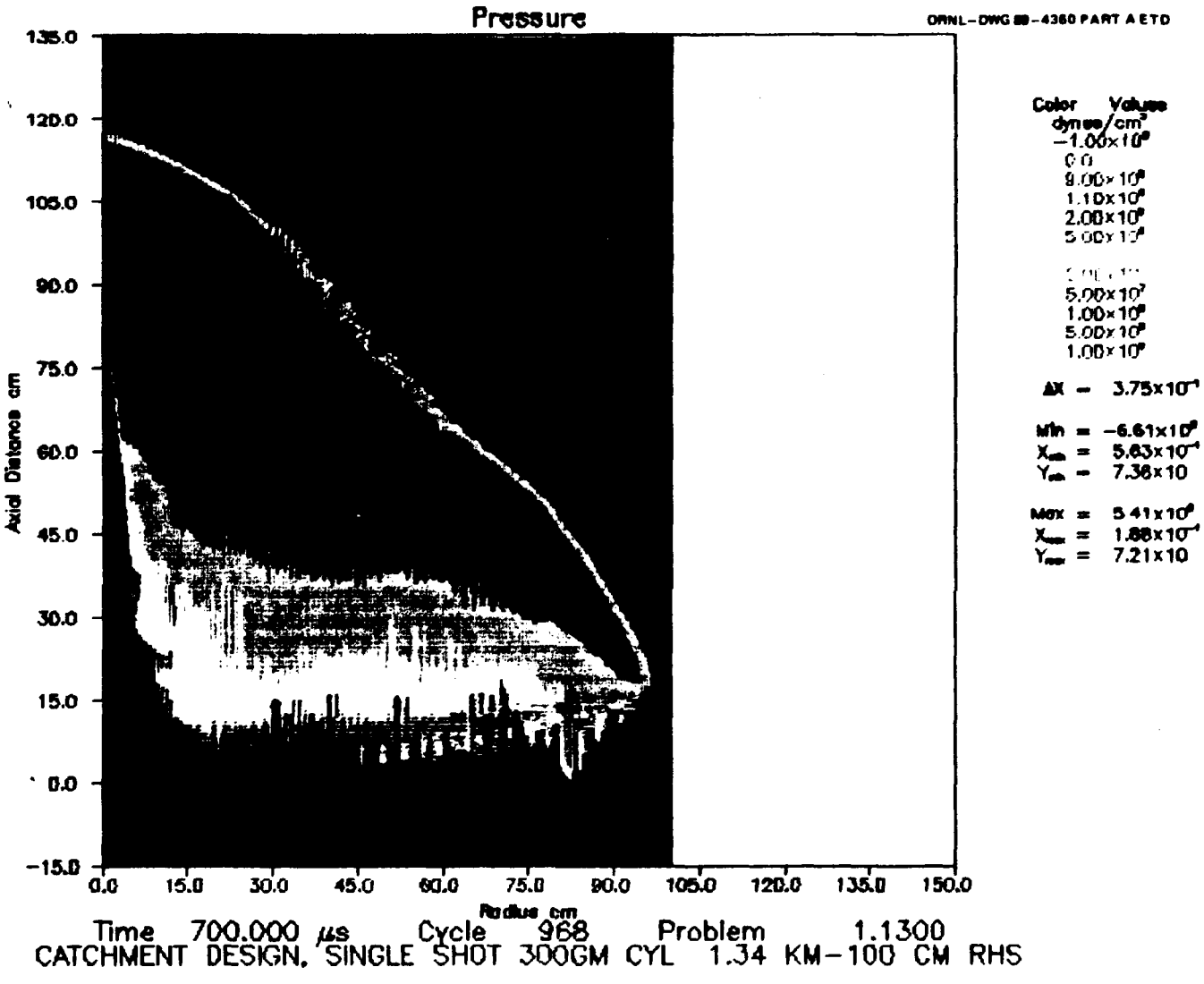

FIGURE 20. Plate 1, 0.7 ms (Prior to Pressure Wave Reaching the Wall).

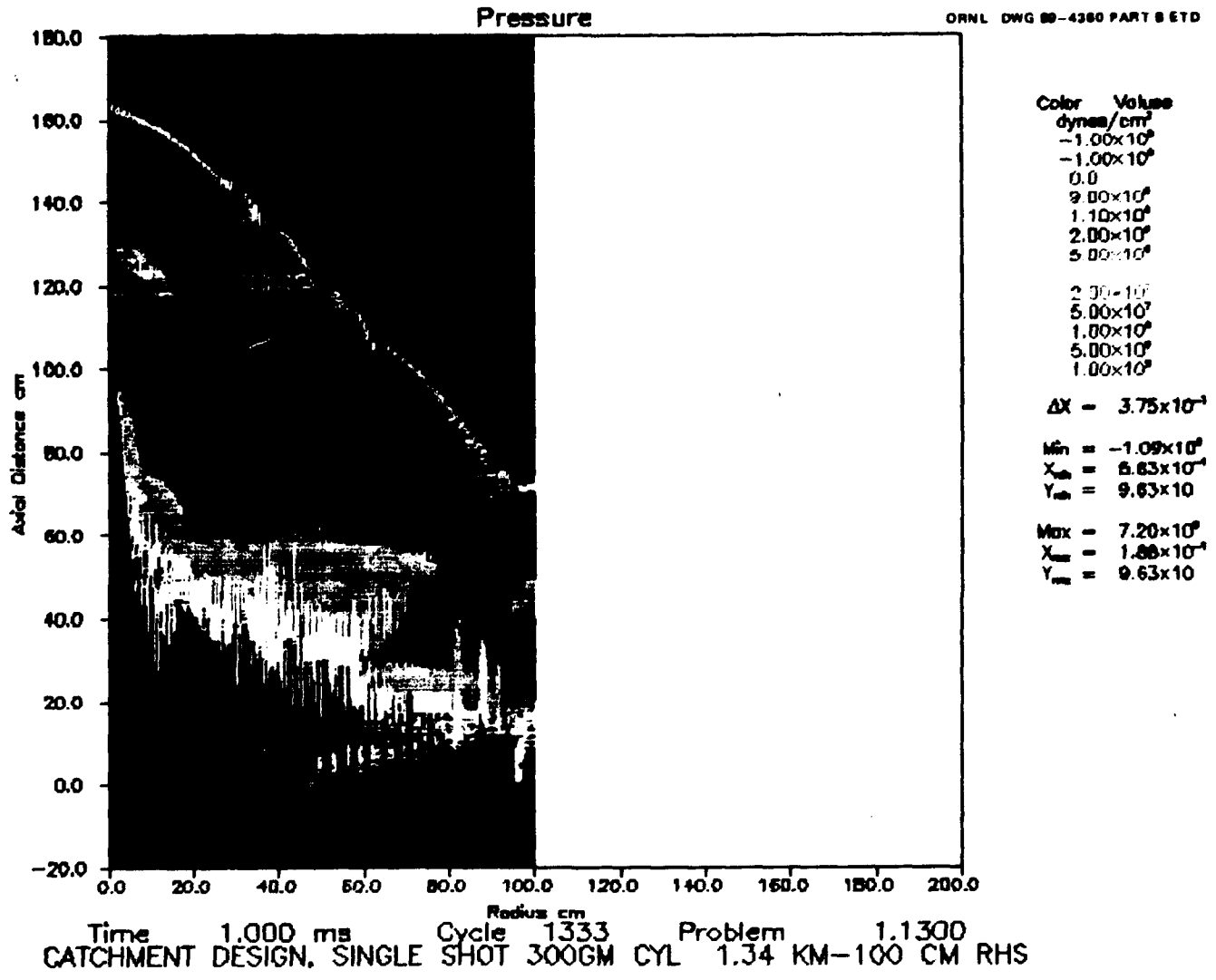

FIGURE 21. Plate 2, 1.0 ms (Pressure Wave Just Reaches Wall).

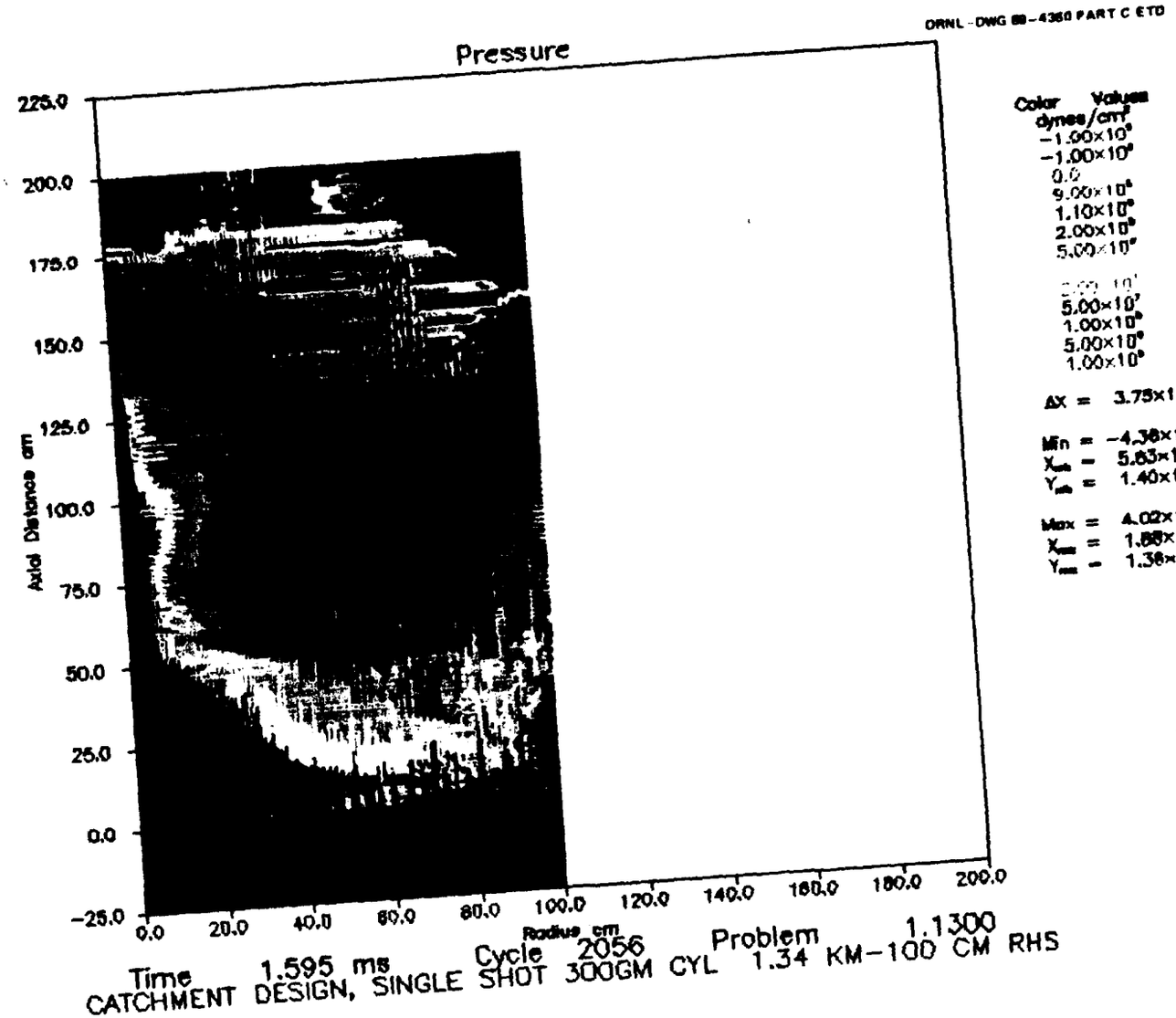

FIGURE 22. Plate 3, 1.595 ms (Showing the Start of a Complex Pattern of Pressure Reflections).

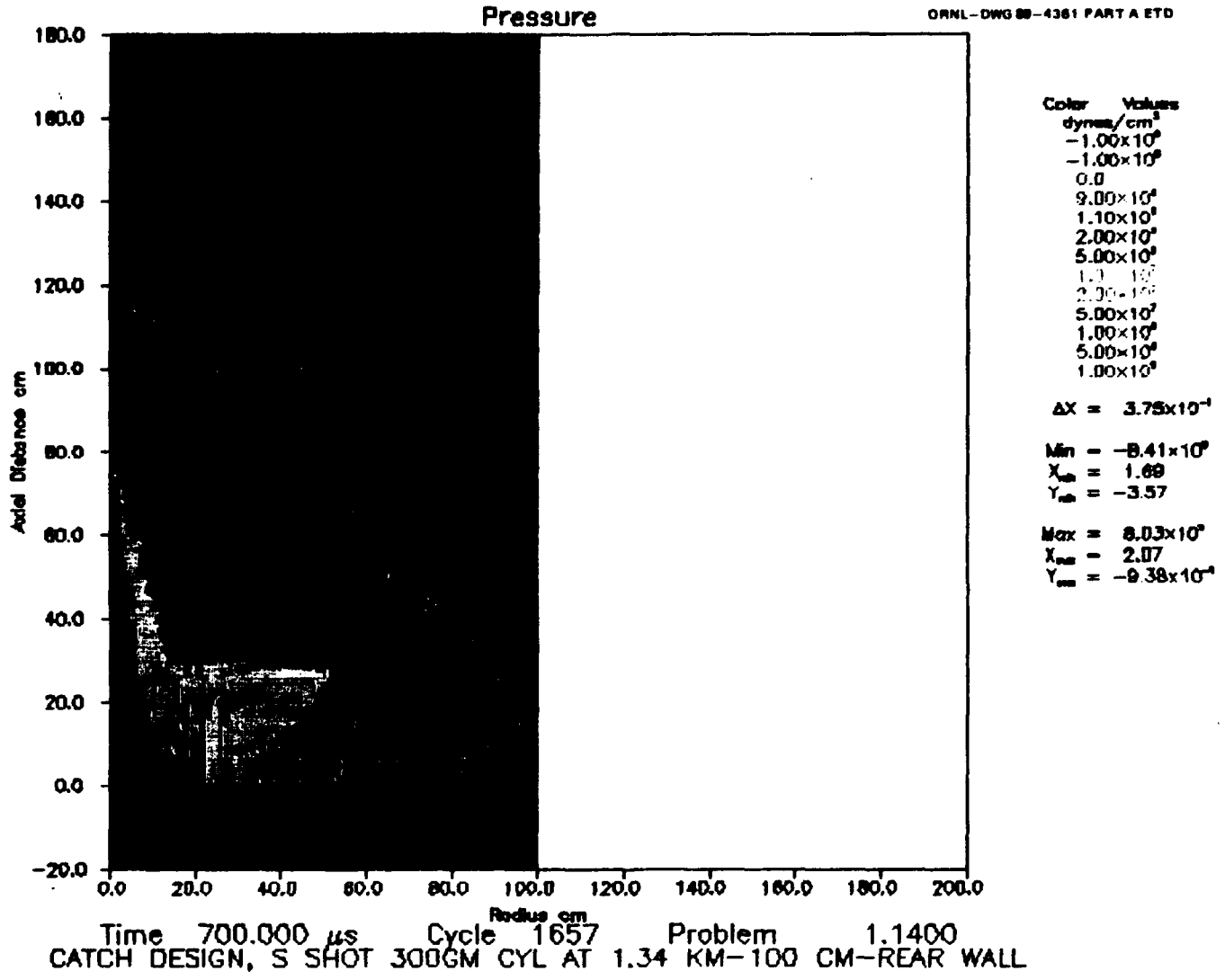

FIGURE 23. Plate 1, 0.7 ms (Prior to Pressure Wave Reaching the Wall).

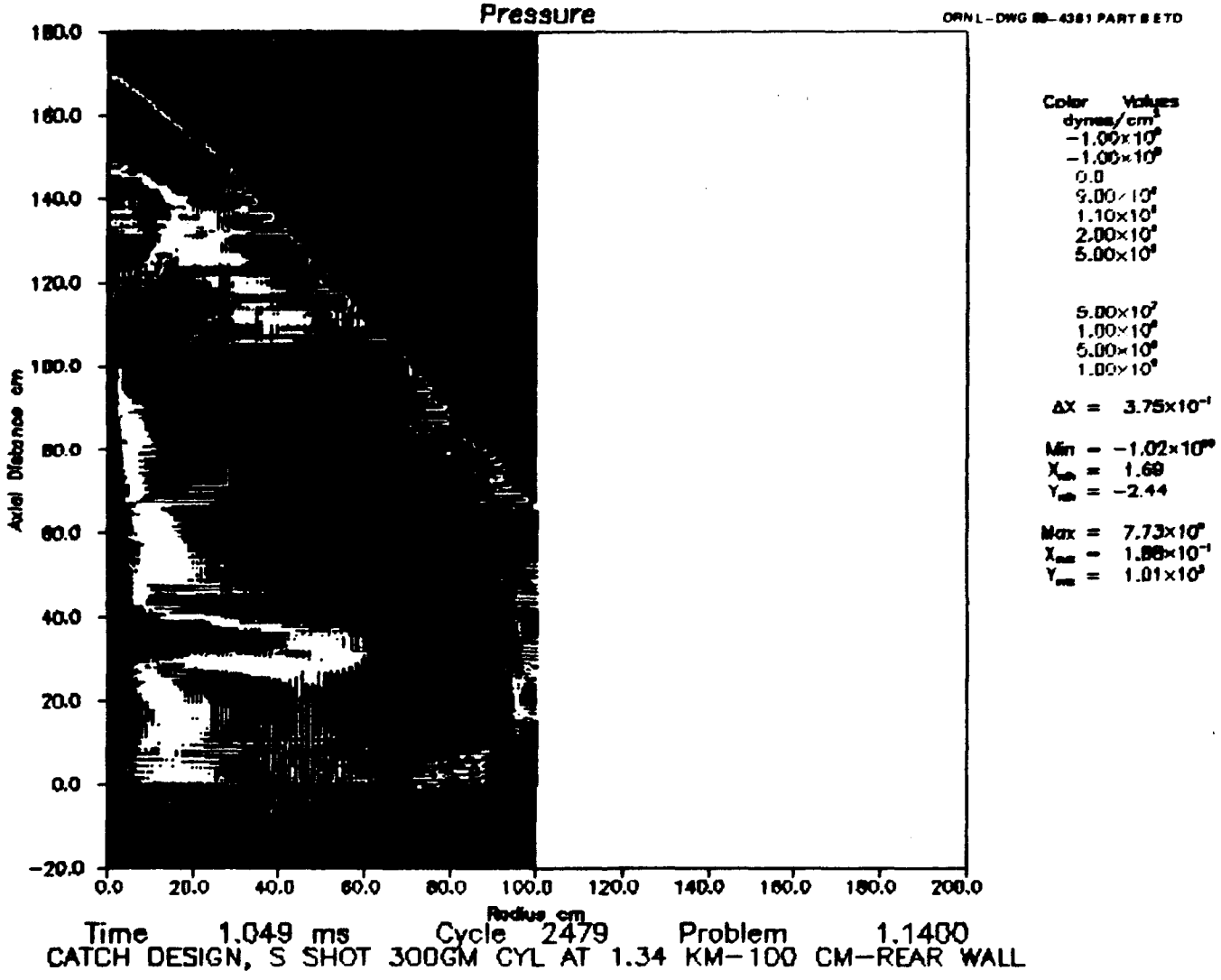

FIGURE 24. Plate 2, 1.049 ms (After Pressure Wave Reaches Wall).

(3) No information is discerned regarding the key area of wake collapse rate for the two cases because of the short, real-time duration covered.

(4) For the "open" catchment case, wall pressure traces as well as the fringe plots (Figures 20-24) indicate a peak impact pressure in excess of 5.0 MPa and ~8 MPa (1200 psia). The "closed" catchment pressure patterns indicate more extensive pressure zones exceeding 10 MPa (1500 psia) but <50 MPa (7500 psia) than for the "open" case at corresponding times. For the "closed" catchment, wall pressure impacts somewhat in excess of 10 MPa (1500 psia) are predicted.

8. Conclusions Regarding Alternative Catchment Media

a. Only two alternative media have been identified as potentially satisfying criteria deemed suitable for basically a gun test facility — ice and water. These criteria are cited in Section VIII.A.1.

b. Examination of ice catchment systems indicates that it is probably <u>not</u> a suitable alternative stopping medium for this application. The criterion for "improved catchment operation" would not be satisfied because of requirements for intermittent operation and maintenance of a large refrigeration unit.

c. Modification of the existing catchment building for use with ice or water is not deemed to be reasonably feasible.

d. The principal problem in using water as a stopping medium relates to its behavior following a rapid sequence of nearly colinear bullets. A horizontal catchment with a free surface is probably not feasible because of formation of persistent vapor wakes. As a result, excessive stopping lengths would be required for a multiple firing test. Increasing pool depth tends to reduce vapor "cratering," but seemingly, excessive depths would be required.

e. A closed water catchment, that is, one with (almost) no free surface, would have the property of rapid vapor wake collapse. As a theoretical limit for a perfectly closed catchment, voids would be collapsed by water compressibility or reflected pressure waves in less time than the duration between successive bullets. The required stopping length for a bullet sequence would therefore not differ from the requirement for an individual bullet, that is, from 5 to 10 meters.

f. The feasibility of closed catchments depends on whether or not there is a reasonable compromise between the conflicting requirements between closing the catchment volume to eliminate the free surface and allowing the bullets to enter.

g. Computer runs using the HULL code indicate that water catchments need to withstand pressure impacts at the wall in excess of 8 MPa (1200 psi) and probably higher for "closed" catchments. Wake diameters of up to 40 cm (15.8 inch) are indicated for a portion of the bullet trajectory. No information on vapor wake collapse rate was obtained because of the short, real-time duration of the computer runs.

SECTION IX
SUMMARY AND CONCLUSIONS

A. Previous AFATL-sponsored studies relating to improved methods of uranium/sand separation are reviewed in Section III. The most useful of those is the K D Engineering study (Reference 2), which provided some analysis of the contaminated sand and results of bench-scale tests of two dry and six wet separations procedures. The sand analysis (on sand that had already been sifted through a 1/2-inch screen) showed the uranium/ to be concentrated in the large particle fractions (>20-mesh) and, to a lesser extent, in the fines (sizes <65-mesh).

B. Many solids separations procedures function best on feeds that contain a reasonably narrow range of particle sizes. Therefore, a likely first step in an improved uranium/sand separations scheme would be size classification by sieving. This would also serve to preferentially remove uranium from the bulk of the sand in the large (>10-mesh) and small (less than about 60-mesh) size fractions. Removal of the fines would be an additional benefit in reducing the tendency for blockage of the HEPA filters in the target building.

C. Following sifting for classification, results of bench-scale tests by Keane (Reference 2) led to a preference for spiral classifiers for further uranium separation. Spiral classifiers were recommended over the other wet separations methods tested including shaking tables, wet magnetic, static belt, moving belt, and jigs. Dry separations methods were not found to be suitable. No separation was achieved using a commercial dry magnetic device, and an electrostatic separations device created excessive dust.

D. The uranium/sand separations flow sheet recommended by Keane (Reference 2), shown in Figure 5, while likely to provide significantly enhanced uranium/sand separation, is thought to be too complex to be suitable for intermittent operation at the test site, particularly by nonspecialized personnel.

E. Other related work reviewed in Section III includes AFATL-sponsored studies by Mallory (Reference 1) on alternate disposal options, an informal report by Crews on jigging tests that sought to reduce contamination levels to <35 pCi/g, and some inconclusive filtration studies by Farrell (Reference 3).[12]

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[12]R. C. Crews, Eglin AFB, unpublished report, August 22, 1986.

F. A study by Hoegler showed promise for dry, magnetic separation of uranium from sand. The degree of separation achieved by Hoegler exceeded that reported for the best wet separator device, the spiral classifier, reported by Keane.[13] The reason for the disparity is not clear at this time, but the Hoegler data should be verified in Task II.

G. A review regarding the potential applicability of uranium mining technology to improved uranium separation at the gun test site is summarized in Section IV and more extensively outlined in Appendix B. There is little potential for application from this technology since it is based on ore dissolution and reprecipitation methods not applicable to the gun test site.

H. The contaminated sand in the butt was sampled in May 1988. Twenty samples of ~400 grams each were acquired from various locations along the butt and at depths up to 3 feet. These samples, plus samples of uncontaminated sand, were analyzed to determine the particle size distribution and the uranium concentration in each size fraction.

I. The results of the sampling and analysis are given in Section IV and in Appendix C. The results show that about 62 percent of the DU in the sand is contained in the coarse fraction, defined as the +10-mesh sizes, which is in general agreement with operational data obtained onsite and with data from Reference 2. Approximately 18 percent of the DU was found in the fines fraction, that is, sizes <60-mesh, which is also in close agreement with Reference 2. Thus, size separation of the coarse and fine size fractions will also remove about 80 percent of the DU.

J. Size distributions of sand obtained from suppliers near Eglin AFB indicates that presifted sand, consisting largely of particles in the -10/60-mesh range, may be obtained for a small cost penalty. About 96 percent of such pre-sifted sand is contained within the -10/60-mesh range, compared to about 83 percent for unsized sand. Use of such pre-sifted sand is expected to significantly reduce the volume of both the coarse and fine disposal streams.

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[13]J. M. Hoegler, "Magnetic Separability of Uranium from Sand," unpublished ORNL report to Eglin AFB, 1987.

K. An evaluation of alternatives for uranium/sand separation following an initial size classification step is provided in Section VI. Table 19 presents attempts at objective evaluation of separations options. Six attributes of wet and dry methods are numerically rated and, after multiplication by a weighting factor, summed to obtain a quantitative "overall performance factor." Wet methods are favored over dry ones because of enhanced ratings for safety, and the spiral classifier appears as the preferred wet method by a small margin.

L. Wet methods require a water handling system, which entails an added cost, especially if there is a chance for water contamination in excess of 40 pCi/mL. The cost of water handling may be considered as a tradeoff against the cost of providing suitable safety and containment for a dry method. The current rating shown in Table 19 may not sufficiently account for water systems cost penalties.

M. Some options for improved uranium/sand separations systems are outlined in Section VII. An improved system must lower operating costs, particularly the cost of disposal, and be suitable for the gun test environment. The recommendations include

1. the use of sized sand with greatly reduced oversizes (>10-mesh) and fines (<60-mesh approximately),

2. an improved sieving procedure that rejects sizes above about 10-mesh and below about 60-mesh, and

3. an additional separations step on the -10/+60 size class, if proven to be cost-effective.

The improved sieving procedure alone referred to in items (1.) and (2.) above and described in Section VII and Figure 13 is projected to remove at least 80 percent of the uranium from the feed to the initial sieve.

N. A second separations step may be added to the improved sieving procedure by some further treatment of the -10/+60-mesh size range prior to recycle to the target. The flowsheet for so doing is illustrated in Figure 14. It is possible that this second separations step would treat only the larger sizes in this range, the -10/+20-mesh size range, where the uranium contamination is expected to be concentrated. The cost-effectiveness of the second-stage separations step will be determined in Phase 3 using bench- scale data obtained in Phase 2 and other estimates of the degree of separation. According to the current evaluation, the preferred second-stage separator

would be a spiral classifier. If a wet system, such as the spiral classifier, proves more costly than currently envisioned, dry options, such as the air classifier or the open gradient magnetic separator (if proven to be effective) would be considered.

O. An evaluation of alternative catchment media is provided in Section VIII. To be acceptable, alternative media must satisfy criteria for ease of uranium separation and safe operation and must also enable a robust system design. These criteria restrict alternative media options to water (or density-enhanced water solutions) and ice. Further examination of ice as a stopping medium indicates that, while it has several potentially attractive features, it leads to operations that are probably not suitable for the gun test site.

P. An evaluation of water (or high-density water solutions) as a stopping medium indicates that adaptation of the current target building to water appears impractical because of generation of high-pressure loadings on the walls resulting from the bullet impacts into the water. However, the principal problem regarding use of water relates to vapor wake formation. The size and rate of collapse of vapor wakes are critical in estimating the required catchment length for a rapid series of nearly colinear bullets. Ordinary water catchments with a large free surface would not be suitable because of excessively slow vapor wake collapse.

Q. There may be some opportunity for accelerating wake collapse to <14 ms (the duration between successive rounds) by use of a "closed catchment," that is, one that contains minimal free surface. Water in such a catchment would be compressed by the bullet impact and would rebound in <14 ms to collapse the vapor wake. It is not clear, however, if nearly closed catchments (i.e., with some free surface to allow bullet entry) would sufficiently retain this property.

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2. J. M. Keane, Recommended Procedure for Uranium-Containing Waste Separation, AFATL-TR-83-85, Air Force Armament Laboratory, 1983.

3. L. T. Farrell, Filtration System for Removal of Depleted Uranium from Water, AFATL-TR-87-66, Air Force Armament Laboratory, 1988.

4. G. R. B. Elliot, DU Cleanup of Target Sand, LAC 83-11, Los Alamos Consultants, October 1, 1983.

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APPENDIX A
LOG OF MONTHLY OPERATIONS OF THE TAC-64 GUN TEST FACILITY

TABLE A-1. TAC-64 DU TEST OPERATIONS LOG (LARGE BUTT)

Month	Rounds fired	Weight (kg)	Target cleaned
January 1979	1637	490	
February	4816	1442	
March	0	0	
April	0	0	16 April 79
May	4176	1250	
June	3078	921	
July	0	0	
August	0	0	
September	162	48	
October	0	0	29 October 79
November	8032	2405	
December	0	0	
January 1980	1248	374	22 January 80
February	3401	1018	
March	1450	434	
April	1980	593	
May	1353	405	
June	3077	921	
July	8	2	15 July 80[a]
August	0	0	
September	4544	1360	
October	15724	4707	
November	0	0	
December	0	0	
January 1981	0	0	
February	0	0	
March	0	0	
April	0	0	
May	0	0	
June	0	0	
July	1799	539	
August	8585	2570	
September	8524	2552	
October	8413	2519	
November	0	0	
December	0	0	

Table A-1 (CONTINUED)

Month	Rounds fired	Weight (kg)	Target cleaned
January 1982	0	0	
February	0	0	22 February 82
March	3084	932	
April	0	0	
May	0	0	
June	0	0	
July	21	6	
August	0	0	
September	1842	551	
October	4169	1248	
November	3916	1172	
December	1215	364	
January 1983	4084	1223	
February	4944	1480	
March	0	0	
April	0	0	
May	0	0	
June	0	0	
July	0	0	
August	0	0	
September	0	0	
October	0	0	
November	0	0	
December	247	74	
January 1984	0	0	
February	0	0	
March	0	0	8 March 84
April	0	0	
May	0	0	
June	623	187	
July	0	0	
August	1743	522	
September	2214	663	
October	1517	455	
November	0	0	
December	0	0	

Table A-1 (CONTINUED)

Month	Rounds fired	Weight (kg)	Target cleaned
January 1985	0	0	
February	0	0	
March	16	4.8	
April	1073	321.9	
May	0	0	
June	4099	1229.7	
July	7730	2319.0	
August	4622	1386.6	
September	0	0	
October	606	181.8	
November	0	0	
December	0	0	
January 1986	0	0	
February	0	0	
March	0	0	
April	0	0	24 April 86
May	544	163.2	
June	4008	1202.4	
July	4268	1280.4	
August	3358	1007.4	
September	4267	1280.1	
October	3816	1144.8	
November	3051	915.3	
December	0	0	
January 1987	0	0	
February	0	0	
March	0	0	
April	0	0	
May	0	0	4 May 87
June	0	0	
July	244	73.20	
August	5165	1549.5	
September	0	0	
October	0	0	
November	0	0	
December	0	0	

Table A-1 (*CONCLUDED*)

Month	Rounds fired	Weight (kg)	Target cleaned
January 1988	0	0	
February	0	0	
March	0	0	
April	0	0	
May	0	0	
June	320	96	
July			
August			
September			
October			
November			
December			

[a]Complete cleanout; replaced with new sand.

APPENDIX B
REVIEW OF URANIUM MINING TECHNOLOGY FOR METHODS OF URANIUM/SAND SEPARATION AND SOLIDS HANDLING

A. INTRODUCTION

In order to evaluate the technologies used in uranium sand separation, a literature review was conducted on uranium mining technology. The emphasis was placed on the methods of separation used. Many of the physical methods that may be useful have been found to be still in the R&D phase in bench-size units. We thought it would be useful to include a summary of the results from these tests since this information is important for evaluation purposes.

B. URANIUM MINING PROCESSES

Uranium is found in high concentrations in rocks that are rich in silicates in minerals such as uraninite, pitchblende, cleveite, brannerite, and davidite. The sandstone-type resources in the United States have a uranium content of 0.04-0.2 percent.

As an initial step, the ore generally undergoes a preconcentration stage that enriches low-grade material to a point where it can be processed economically. This may be done by electronic sorting devices in which a Geiger counter mounted above a slow-moving conveyor actuates a cylinder-operated pusher to remove either barren or radioactive pieces from the conveyor. This is followed by crushing and grinding in which uranium values concentrated in the cementing material are separated from the barren sand. This may be followed by a roasting or calcining at high temperatures to oxidize the material to a better form for leaching. Treatment with suitable solvents (acids or alkalies) converts uranium to a water-soluble form. Most mills use acid leaching, which completely extracts uranium. Usually sulphuric acid is preferred. Sometimes, as with minerals such as pitchblende, this dissolution has to be carried out under oxidizing conditions provided by addition of oxidants such as manganese dioxide or sodium chlorate. The uranium is then separated from the leach liquors by ion exchange or by extraction.

C. URANIUM SEPARATION TECHNIQUES IN THE MINING INDUSTRY

Information from the literature in the uranium mining industry on evaluation of various separation techniques is summarized in the following sections. The material selected is not comprehensive. Processes that were most relevant to the problem at hand were selected.

1. Chemical Methods

The uranium is usually extracted from the ore by chemical leaching. The type of chemical method employed usually depends on the type of ore.

In Canada, as reported by Thunaes (Reference B-1), three principal systems have been in use:

a. Sulphuric acid leaching of pitchblende ores at controlled pH level 1.5 to 1.8 for 24 hours at ambient temperature using sodium chlorate oxidant followed by recovery of uranium from solution by ion exchange or solvent extraction.

b. Sulphuric acid leaching of brannerite ores with acid at 5 percent weight concentration with long retention times and higher temperatures. This is followed by recovery of uranium by ion exchange. All mines in the Elliott Lake district are treating brannerite ores, and 90 percent of known Canadian reserves of uranium are of this type.

c. Sodium carbonate leaching of pitchblende ore, with recovery from solution as sodium diuranate.

Ore processing in India is described by Farreeduddin in Reference B-2. The ore is of low grade with typically about 0.04 to 0.08 weight percent U_3O_8. Maximum recovery of uranium (90-95 percent) is obtained only with an acid consumption of about 90 kg of sulfuric acid per ton of ore. About 7 kg of manganese dioxide was used for oxidation per ton of ore. The resultant uranium dissolved was extracted by ion exchange.

South Africa has a large effort in processing of uranium ores by chemical means, as described by Robinson in Reference B-3. In all cases, the uranium plants use an acid leaching processing using sulphuric acid with manganese dioxide, followed by ion-exchange treatment of the leach solutions produced. The ion-exchange eluates are treated first with lime (CaO) to precipitate iron, after which uranium is precipitated with ammonia to give a product which, after calcination, contains ~90 percent U_3O_8. Initially, all plants treated the residue from the gold recovery plants. Fairly recently, however, several plants have converted to a "reversed leach" procedure in which the uranium is extracted first, followed by gold extraction by cyanidation. The essential advantage of this reversed leach is to eliminate the formation of cobalt-cyanide complexes, which act as severe resin poisons.

There have been modifications to the standard leach procedure in South Africa in which a "ferric leach" process has been adapted at one plant. In this modification, a portion of the uranium-free leach solution (after ion exchange) is rejected,

and sulfuric acid and ferric ions are regenerated by the introduction of SO_2 and oxygen to the solution.

There is some development work on the combined gold-uranium leaching process. The essential feature of this work is the use of alkaline leach solutions containing sodium carbonate and sodium bicarbonate, a suitable oxidant, and cyanide ions. From the point of view of gold extraction, the process is exactly analogous to the conventional cyanide process using lime and sodium cyanide except that the alkali-lime is replaced by sodium carbonate.

Peterson describes the methods of leaching uranium in Sweden in Reference B-4. There are very large, low-grade uranium ore deposits in Sweden which are present in alum shale. After the uranium ore is crushed and sized, it is weathered in a process by which the uranium is oxidized from the tetravalent to the hexavalent stage. Because of this process, a higher yield is obtained in the leaching process. The profitable effect of the weathering is favored by oxygen, water, and increased temperature in the surroundings. Based on laboratory experiments, the optimal storage time was calculated to between 2 and 3 weeks. The leaching is carried out in four 25- X 25- X 5-meter concrete basins. The basins contain 2000 tons of shale each, and one basin is loaded every day. The basin walls are lined with a sheet of neoprene rubber covered by acid-resisting brick work. The basins have filter bottoms of granite stone rows, between which are several layers of gravel. The leaching is done with sulphuric acid.

The shale from the weathering pile is heated and moistened directly with steam to a temperature of ~70°C and passed into a leaching basin. The uranium is extracted with D2EHPA in kerosene at 40°C (10 percent D2EHPA, 5 percent TPB, 85 percent kerosene) and is reextracted from the organic phase at 40°C with sodium carbonate solution (80 g/L Na_2CO_3). The uranium is
precipitated from this solution at 80°C with diluted sodium hydroxide. After meshing, the precipitate is thickened and dried in an electric dryer.

In the United States, the recovery of uranium from low-grade sandstone ore and phosphate rock by leaching is described by Kennedy in Reference B-5. The treatment of low-grade sandstone rocking containing 0.02 to 0.1 percent U_3O_8 is accomplished by heap leaching of the mined rock either at the mine site or at the mill if ore transportation costs are not excessive.

The leaching solution consists of 2-2.5 g/L of iron and 10 g/L sulfuric acid. This solution is pumped into the shallow ponds on a heap of ore and allowed to trickle through the bed.

Recoveries are on the order of 50 to 80 percent. The uranium is usually recovered by ion-exchange resin.

2. Flotation

Flotation for mineral recovery uses froth for separating finely ground valuable minerals from their associated gangue. The process is based on the affinity of properly prepared surfaces for air bubbles. A froth is formed by introducing air into a pulp of finely divided ore in water containing a frothing or foaming agent. Minerals with a specific affinity for air bubbles rise to the surface in the froth and are thus separated from those that sink in water. In preparation, the ore must first be ground to liberate the intergrown valuable mineral constituent from its worthless gangue matrix.

A summary of flotation experiments of separating uranium from uranium ores in Canada is given by Muthuswami et al. in Reference B-6. In this study, the uranium had to be extracted from the ores as well as ^{230}Th and ^{226}Ra, which are the accompanying daughter radionuclides, so that a recommended level of 20 pCi/g of ore was attained, which is safe for disposal. Froth flotation is a powerful technique to concentrate the uranium mineral and the associated radionuclides and to leave the bulk of the ore as safely disposable tailings that require neither monitoring nor further treatment. Yet for flotation to be selective and economically attractive, an astute choice of chemicals as collector agents and operating conditions is required.

Based on an analysis of the Elliott Lake ore, the ideal is to preconcentrate all the uranium and pyrite in about 6 percent of the ore mass. A recovery of 97 percent uranium and most of the pyrite in about 15 percent ore weight has been suggested as an economically viable goal under the present market conditions. If flotation agents can be selected and conditions chosen so that the radium could be concentrated with uranium, then for a feed of 300 pCi/g, the levels would contain 10.6 pCi radium/g. This is below the 20-pCi/g requirements for disposal of tailings.

One of the most efficient preconcentration methods for low-grade uranium was that by Raicevic and co-workers (Reference B-7) and Sirois et al. (Reference B-8), who demonstrated that a combination of pyrite flotation and high gradient magnetic separation (HGMS) achieved excellent results of uranium recovery of 87.9 percent, 96.5 percent, 97.4 percent, and 97.9 percent in 22.2, 29.7, 34.8, and 40.1 mass percent of combined concentrates, respectively. Muthuswami's (Reference B-6) goal was to achieve the same separation of uranium as Raicevic et al. (Reference B-7) but without the use of HGMS. The composition of the one used by Muthuswami (Reference B-6) is shown in Table B-1. Of all the

agents that were timed, cupferron [$C_6 H_5 . N(NO) \cdot ONH_4$] gave the most promising results. Most runs with cupferron at a pH of 5 to 6 gave attractive recoveries of 92 percent of uranium in 25 percent of mass. Runs using other reagents requiring low pH made the uranium more soluble, which is an undesirable result.

In a study by Daud and Bahari (Reference B-9), uranium ore from Larap, Panganibom, and Norte in the Philippines was studied for laboratory tests involving magnetic separation followed by flotation tests. The magnetic separation was employed to remove the magnetite from the heavy mineral concentrate, and the flotation method was used for separation of sulfide.

The ore had the following composition: magnetite (Fe_3O_4), 45 percent; pyrite (FeS_2), 2 percent; Cu, 1.2 percent; Mo, 0.22 percent; and U_3O_8, 0.04 percent. The flotation operation involved removal of sulfides by using a Denver Laboratory flotation machine model D-1. The pulp (slurry) density was fixed at 35 percent solid, and the pH was maintained at 8.5. Since the pH of the pulp ranged from 7.2 to 7.4, 0.5 kg of lime per ton was needed to raise the pH to 8.5.

TABLE B-1. COMPOSITION OF URANIUM ORE USED BY MUTHUSWAMI (REFERENCE B-6)

Constituent	Percent
U	0.08
Th	0.04
S	2.0
P_2O_3	0.09
MnO	0
TiO_2	0.32
K_2O	2.8
Na_2O	0.11
Ca	0.2
MgO	0.17
Fe_2O_3	2.5
Al_2O_3	8.8
SiO_2	83

The speed of the flotation machine was kept at 1500 rpm. The residence time in the flotation machine was 14 minutes. The collector chemical was sodium isobutyl xanthate, with a usage rate of 50 g/ton of ore. The frother used was Hoe F2711, and its consumption was 40 g/ton. These conditions resulted in a recovery of U_3O_8 at about 98 percent in the tailings in all the samples that were treated for the flotation tests.

3. Magnetic Methods

In bench-scale and pilot-scale tests, it was shown that wet, high-intensity magnetic separation (WHIMS), Figure B-1, achieved good recoveries of gold and uranium from Witwaters sand residues in South Africa (Reference B-10). Using residues from cyanidation and some ores and flotation tailings from the uranium and gold waste, a production size process using WHIMS was used to separate the uranium and gold from the residues.

A previous mechanical problem was the tendency of the high gradient producing matrix of iron balls (6 mm in diameter) within the separator to become progressively blocked with ferromagnetic material and fine wood fibers. A solution to this problem was obtained by development of a washing system that permits the balls used in the matrix to be continuously removed from the machine and, after being washed in a trommel screen, returned to the separator. With the washing system installed, several successful pilot-plant operations were carried out on cyanidation tailings from a mine in the Klerksdorp area. Typically, 55 percent of the gold and 45 percent of the uranium was recovered into a magnetic concentrate that was 14 percent by mass of the original feed.

On the strength of the pilot-plant results, the mining group that had supported the tests decided to purchase and install two full-size WHIMS machines, each of which was fitted with the washing system described.

The treatment of the wastes from the gold mine operation is described in the flow sheet in Figure B-1. In this operation a sample of residue is taken from the cyanidation plant and delivered onto the vibrating screen to remove as much of the wood-chip fiber as possible. The slurry (at a relative density of 1.4) is fed to the screen at a rate of 55 ton/h. The 1.8-m^2 screen was fitted with a screen deck having 1-mm-square openings. The screen underflow passes to a 6-m^3 mixing tank, where the relative density is adjusted to 1.09 before the slurry is pumped to the desliming cyclones, which are arranged as a nest of polyurethane cyclones, each 100 mm in diameter. The cyclone underflow passes to a holding tank, where water is added to adjust the relative density to 1.35. The slurry is then fed by gravity flow to the magnetic separator.

Two products were delivered by the WHIMS machine, a nonmagnetic tailing and a magnetic concentrate. The concentrate was first dewatered and then pumped to the operating extraction plant for the recovery of the gold and uranium.

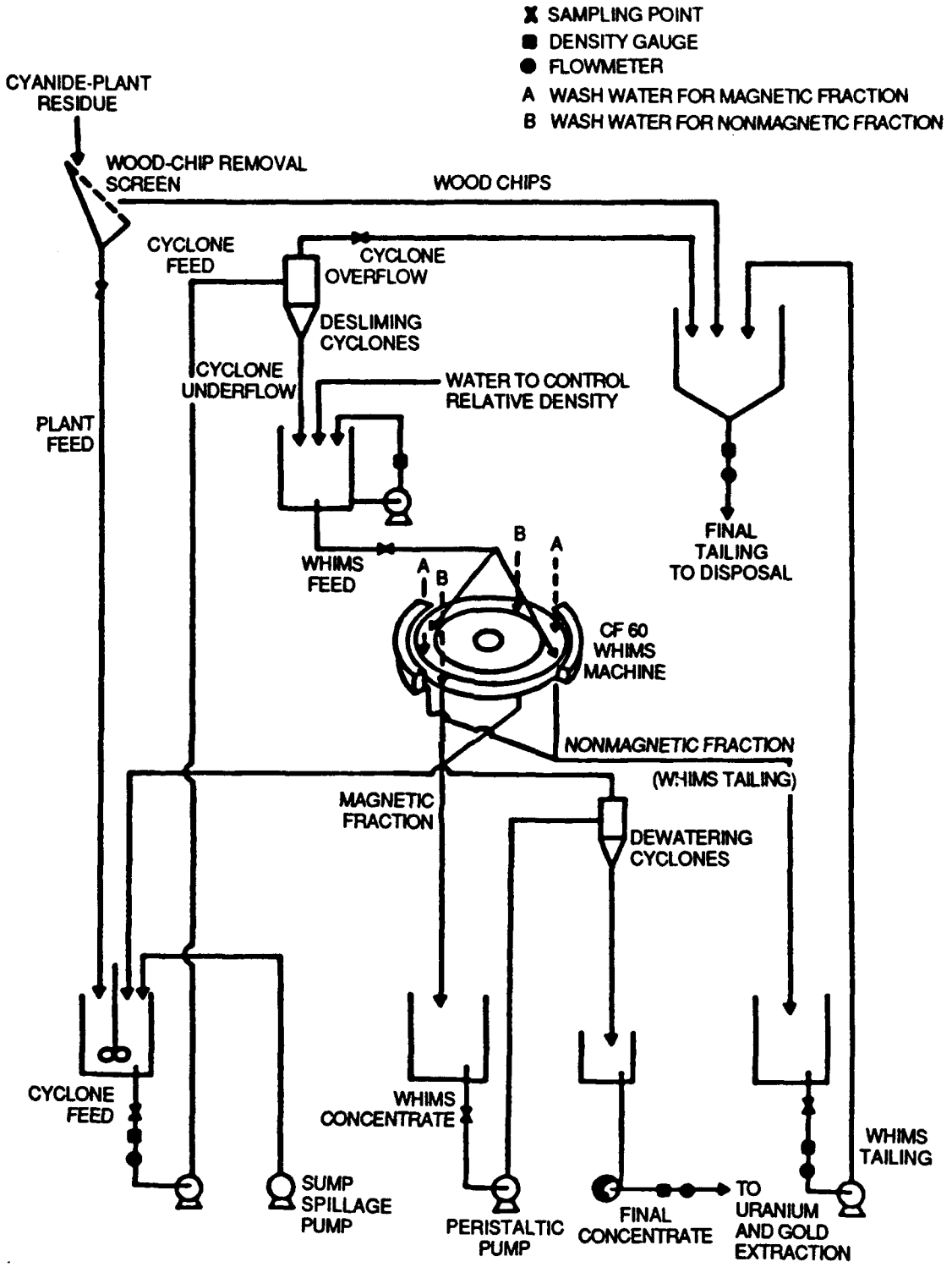

FIGURE B-1. Flow Sheet of the WHIMS Installation.

The WHIMS machine, an Eriez CF-60 model, is illustrated in Figure B-2. This is a double-pole type, the magnetic field being produced electrically in coils wound around an iron yoke. The carousel passes through gaps in the yoke, where the magnetic separation takes place. The outer diameter of the carousel is 3546 mm, and the matrix space is 150 mm wide and 200 mm deep. The carousel, which rotates at 1.5 rpm, has an inclined retaining grid fitted at the bottom and a flexible belt that retains the matrix of iron balls, which are 6 mm in diameter. The balls are removed for washing at one point and are passed through a trommel screen and washed with water sprays before being returned to the machine. The system for washing and returning the balls is illustrated in Figure B-3.

The maximum flux density of 1.0 T (telsa) could be produced in the air gap; however, the machine was normally run at 0.75 by the use of a different tapping on the windings.

The CF-60 was designed to treat 30 tons of dry solids per hour in a slurry of 40 percent solids (i.e., 15 ton/h at each pole pair). After the pulp has passed through the matrix between the poles, water is added to rinse any adhering nonmagnetic material. At a point outside the field, the matrix is again washed with water to remove most of the magnetic material. (The external ball-washing system is designed to remove the remaining magnetic material.)

The desliming cyclones performed well but were a continual source of trouble since the inlets and spigots were subject to blockage with scale that had broken loose from the inside of the pipes.

One of the most serious problems encountered on the WHIMS machine was a fairly rapid buildup of lime-scale on the grates that retain the balls in the carousel. This scale had a detrimental effect on the performance of the machine since it tended to impede the discharge of slurry from the matrix and thus reduced the effective feed rate. Acid cleaning at frequent intervals was required to remove this scale.

The average particle-size distribution of the feed to the desliming cyclones is shown in Table B-2. The complete mass balances for the cyclones for U_3O_8, gold, and sulphur are given in Table B-3. The upgrading of U_3O_8 in the cyclone overflow stream should be noted.

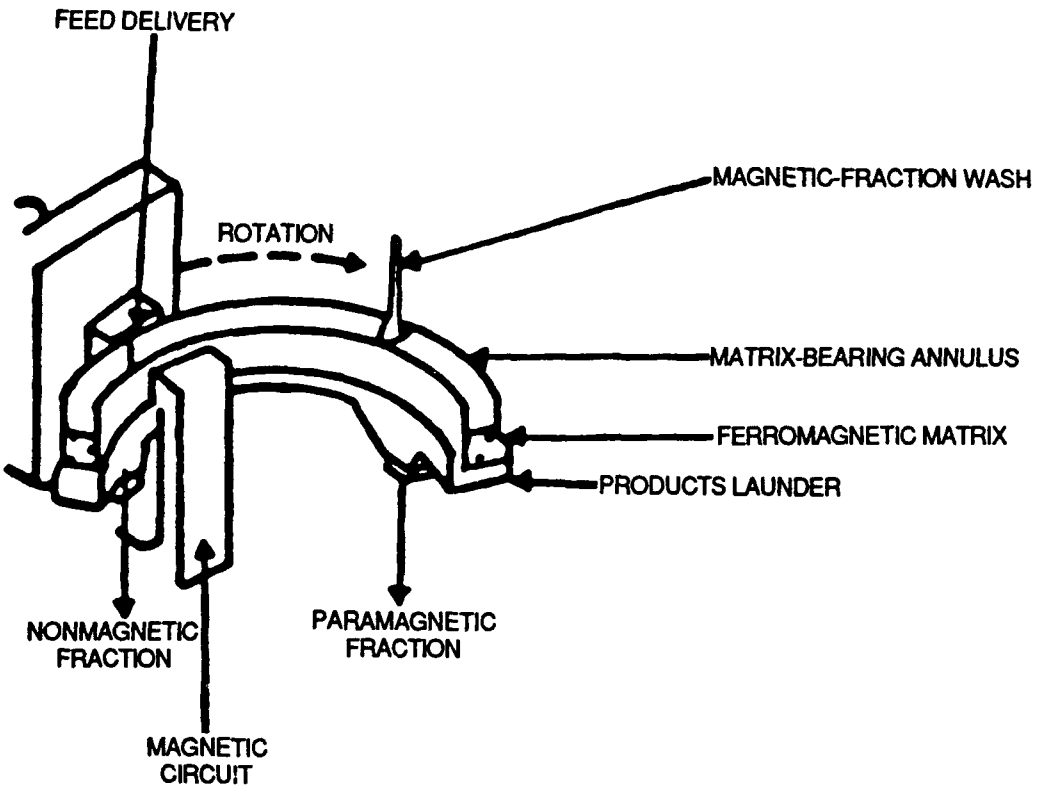

FIGURE B-2. WHIMS Machine Schematic.

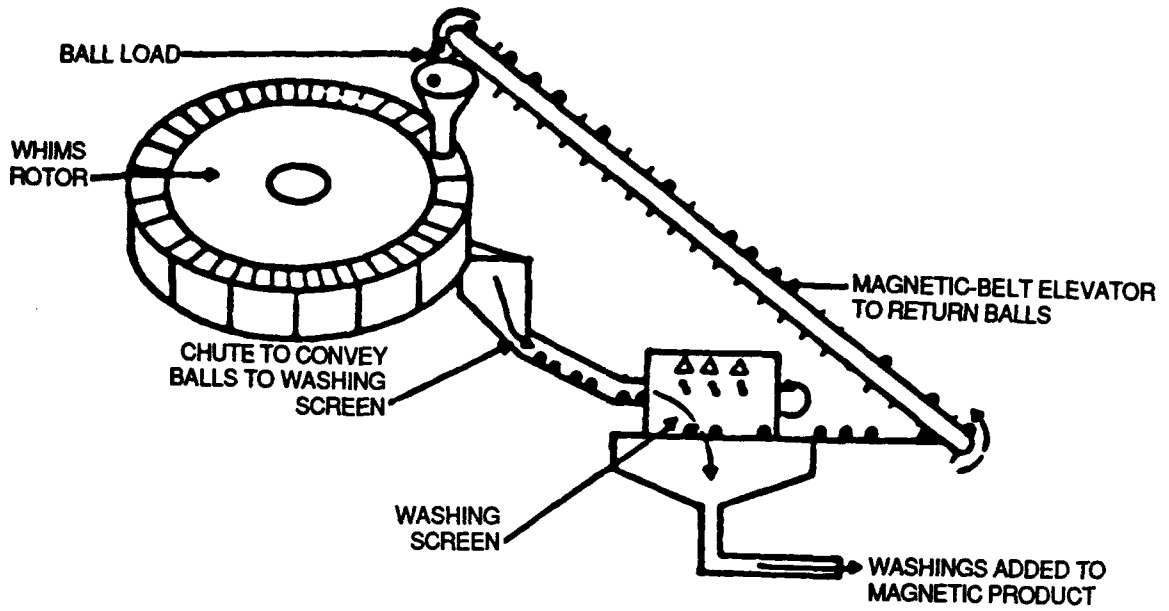

FIGURE B-3. WHIMS Rotor Showing the Cleaning and Ball Return Systems.

TABLE B-2. AVERAGE PARTICLE SIZE DISTRIBUTION OF CYCLONE FEED

		% passing particle size indicated		
Test	Year	<75 mm	<27 mm	<12 mm
Plant tests	1981	84.4	60.1	40.1
Pilot-plant tests	1978	79.6	45.9	31.0

The mass balance for the WHIMS machine and for the whole plant is given in Table B-4. This indicates that the operating WHIMS machines gave fair recoveries of gold and U_3O_8. An overall flowsheet for material balance is given in Figure B-4.

High-gradient tests using a superconducting magnet were conducted by Ballhorn, Rassi, and Watson (Reference B-11) on the Canadian uranium ore known as Cangill carbonatite from the regions of Ontario and Quebec. The separator consisted of a superconducting solenoid capable of producing fields of up to 8 T in a 73-mm-diam room temperature bore. Tests with wet and dry matrix were performed. The wet separation matrix was made of woven mine mesh. In the dry separation process, the matrix used was the same as that in the wet process although the filter arrangement was different. The average distance between the layers of wire mesh was 3 mm, and the total length of the filter was 16 cm. The sample was introduced at the top of the separations tube 33 cm from the matrix through a dispenser and subsequently travelled through the filter under gravity.

The sample was split into three equal parts, ground to three different sizes of <500 μm, <200 μm, and <63 μm. The size distributions are given in Table B-5. The conditions and results of the wet HGMS tests are given in Tables B-6 and B-7, respectively. It can be seen that for grain size <200 μm, about three times as much uranium was concentrated in the "mags" as "nonmags" at a field strength of 6 T. However, for finer grain sizes of <500 μm, the separation achieved was not as good.

For the dry HGMS tests, the conditions and results are given in Tables B-8 and B-9, respectively. The separation in these tests for uranium is better for <500 μm. The separation is also slightly greater than that of the wet tests.

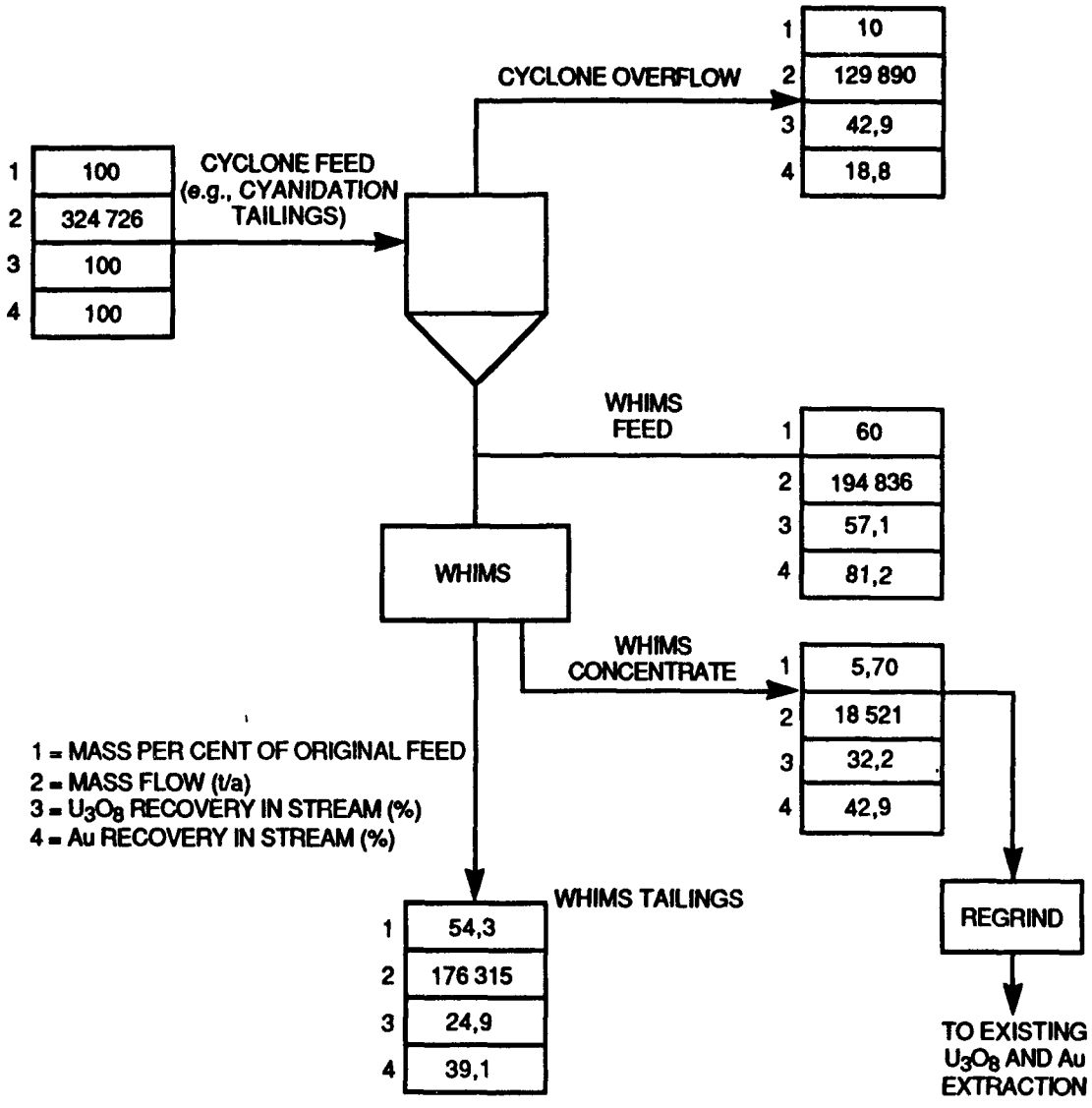

FIGURE B-4. Mass Flow and Recoveries on a Gold Mine.

TABLE B-3. MATERIAL BALANCE FOR DESLIMING CYCLONES

Material	Mass flow of solids (ton/h)	Mass (%)	Assay U_3O_8 (ppm)	Assay Au (g/ton)	Assay S (%)	Distribution of feed U_3O_8	Distribution of feed Au	Distribution of feed S
Feed	53.4	100	172	0.308	0.308	100	100	100
Overflow	20.4	37.9	210	0.144	0.826	43.8	18.4	29.6
Underflow	33.0	62.1	164	0.363	1.2	56.2	81.6	70.4
Calculated feed			181	0.283	1.06			

TABLE B-4. MATERIAL BALANCE FOR THE WHIMS MACHINE

Material	Mass flow of solids (ton/h)	Mass (%)	Assay U_3O_8 (ppm)	Assay Au (g/ton)	Assay S (%)	Distribution of feed U_3O_8	Distribution of feed Au	Distribution of feed S
Feed	33	100	164	0.36	2.07	100	100	100
Concentrate (magnetic fraction)	5.01	15.2	633	1.32	2.07	56.4	51.4	25.1
Tailings (non-magnetic fraction)	28.0	84.8	84	0.21	1.08	43.6	48.6	74.9

TABLE B-5. GRAIN SIZE DISTRIBUTION SPLITS FOR FEEDS IN WET AND DRY HGMS TESTS

<500 μm		<200 μm		<63 μm	
Size interval (mm)	Wt %	Size interval (mm)	Wt %	Size interval (mm)	Wt %
>0.315	13.7	>0.125	21.4	>0.045	23.5
0.315-0.200	21.6	0.125-0.090	16.0	0.045-0.032	15.0
0.200-0.125	13.7	0.090-0.063	12.3	<0.032	61.5
0.125-0.090	7.0	0.063-0.045	5.3		
0.090-0.063	5.2	0.045-0.32	5.3		
0.063-0.045	2.7	<0.032	39.7		
0.045-0.032	2.5				
<0.032	33.6				

TABLE B-6. WET HGMS CONDITIONS

Test No.	Grain size (μm)	Magnetic field (T)	Flow velocity (cm/s)	Weight (%) Mags	Nonmag	Loss
W1	<63	4	5.7	52.0	41.5	6.5
W2		4	11.9	28.8	64.9	6.3
W3	<200	4	8.6	28.3	64.5	7.2
W4		6	23.8	25.0	61.2	13.8
W5	<500	4	7.2	80.3	6.3	13.4
W6		6	23.8	30.0	41.2	28.8

TABLE B-7. WET HGMS RESULTS

Test No.	Uranium (ppm) Mags	Nonmags
W1	426	410
W2	652	325
W3	705	297
W4	854	297
W5	435	586
W6	724	330

TABLE B-8. DRY HGMS CONDITIONS

Test No.	Grain size (μm)	Magnetic field (T)	Flow velocity (cm/s)	Weight (%) Mags	Nonmag	Loss
D1	<63	4	Under gavity	42.6	54.8	2.6
D2	<200	4	Under gavity	25.4	71.8	2.8
D3	<500	4	Under gavity	28.6	64.6	6.8

TABLE B-9. DRY HGMS RESULTS

Test No.	Uranium (ppm) Mags	Nonmags
D1	552	424
D2	793	358
D3	819	219

D. MINERALS-HANDLING TECHNOLOGY

In this section, some of the main features of the minerals-handling equipment will be covered. The main references for an overall detailed description are References B-12 and B-13.

1. Storage Bins and Hoppers

Two important definitions of the flow characteristics of a storage vessel are mass flow, which means that all material moves whenever any is withdrawn, and funnel flow, which occurs when only a portion of the material flows (usually in a channel or "rathole" in the center of the system) as material is withdrawn. Mass-flow bins feature the most desirable characteristics since flow occurs unassisted whenever the bottom gate is opened.

A funnel-flow bin may or may not flow but probably can be made to flow by some means (Reference B-13). Table B-10 compares principal characteristics of mass-flow and funnel-flow bins. A procedure for quantitative design of mass-flow bins is described by Jenike (References B-14 and B-15).

TABLE B-10. PRINCIPAL CHARACTERISTICS OF MASS-FLOW AND FUNNEL-FLOW BINS (REFERENCE B-13)

Mass-flow bins

1. Particles segregate but remit on discharge.
2. Powders deaerate and do not flood when the system discharges.
3. Flow is uniform.
4. Density of flow is constant.
5. Level indicators work reliably.
6. Product does not remain in dead zones, where degradation can occur.
7. Bin can be designed to yield nonsegregating storage or to function as a blender.

Funnel-flow bins

1. Particles segregate and remain segregated.
2. First portion in is last one out.
3. Product can remain in dead zones until complete cleanout of the system.
4. Product tends to bridge or arch and then to rat-hole when discharging.
5. Flow is erratic.
6. Density can vary.
7. Level indicators must be placed in critical positions so they will work properly.
8. Bins perform satisfactorily with free-flowing, large-particle solids.

Many times there is a need for flow-assisting devices in cases where the flow is difficult. Vibrating hoppers are the most versatile flow assisters. They are used to enlarge the storage bin opening and cause flow break-up bridges. Two basic types of vibrating hoppers are common: the gyrating kind and the whirlpool type.

Screw feeders are also used to assist in bin unloading and in producing uniform feed. For uniform flow to occur, the screw feeder opening-to-diameter ratio should not exceed 8.

Belt or apron feeders can be used to give uniform feed from a bin, but care must be taken that dead spots are not produced in the flow channel above the feeder belt (Reference B-13). The capacities of these feeders can be increased by tapering the outlet in the horizontal and vertical planes. To ensure the flow of nonfree-flowing solids along the front bin wall, a sloping striker plate at the front of the hopper is necessary.

2. Conveyors and Chutes

There are several different kinds of conveying systems available, as are described in Reference B-13. The selection of the conveying system depends on the conveying qualities of the material. The material characteristics of common materials is listed in Table B-11, along with classification in terms of properties to be considered for conveying. The different types are briefly described in the following sections.

a. Screw Conveyors

The screw conveyor is one of the oldest and most versatile conveyor types. Based on the conveying characteristics, screw conveyor capacities are listed in Table B-12. However, it should be noted that for sandy, one- mineral type of materials, the screw conveyor may not be suitable because of excessive wear.

b. Belt Conveyors

The belt conveyor is almost universally used. It is most suited for mining operations with ore handling and for abrasive materials.

c. Vibrating or Oscillating Conveyors

Most vibrating conveyors are essentially directional-throw units that consist of a spring-supported horizontal pan vibrated by a directed-connected eccentric arm with rotating eccentric weights. The mechanical vibrating conveyors are designed at specific frequencies and hence are not very flexible to capacity changes. In applications where the production of fines is a concern, these conveyors have the disadvantage of grinding up the minerals to produce more fines.

TABLE B-11. CLASSIFICATION SYSTEM FOR BULK SOLIDS[a]

	Material characteristics	Class
Size	Very fine - <149 mm (100-mesh)	A
	Fine - 149 mm to 3.18 mm (100-mesh to 1/8 in.)	B
	Granular - 3.18 to 12.7 mm (1/8 to 1/2 in.)	C
	Lumpy - containing lumps >12.7 mm (1/2 in.)	D
	Irregular - being fibrous, stringy, or the like	H
Flowability	Very free flowing - angle of repose up to 30°	1
	Free flowing - angle of repose 30° to 45°	2
	Sluggish - angle of repose 45° and up	3
Abrasiveness	Nonabrasive	6
	Mildly abrasive	7
	Very abrasive	8
Special characteristics	Contaminable, affecting use or saleability	K
	Hygroscopic	L
	Highly corrosive	N
	Mildly corrosive	P
	Gives off dust or fumes harmful to life	R
	Contains explosive dust	S
	Degradable, affecting use or saleability	T
	Very light and fluffy	W
	Interlocks or mats to resist digging	X
	Aerates and becomes fluid	Y
	Packs under pressure	Z

[a]From FMC Corporation, Material Handling Systems Division.
Example: A material that is granular, very free flowing, mildly abrasive, and mildly corrosive would fall in classes C, 1, 7, and P, making its classification C17P.

d. Pneumatic Conveyors

This type of conveyor is most important for the chemical industry and employs air or other gas as means of suspending the material to be conveyed. Generally, there are five basic types of conveyors:

(1) Pressure systems
(2) Vacuum systems
(3) Pressure-vacuum systems
(4) Fluidizing systems
(5) Blow tank

Details are described in Reference B-13. However, it should be mentioned that this method of conveying does involve extensive particle abrasion, which may cause attrition and excessive production of fines.

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APPENDIX C
SIZE AND URANIUM DISTRIBUTIONS IN SAMPLED SAND FROM THE BUTT

Size distributions of the 20 samples of contaminated sand acquired from the butt are listed in Table C-1. Sample numbers 1 through 20 identify the samples. The "location" identification indicates the distance in feet from the left wall (facing into the butt), the ground elevation, and depth inward from the face for each sample.

The first row of numbers for each sample gives the mass percent for each of the nine size ranges. The second row gives the uranium concentration, in mass percent, of each size fraction. The third row identifies the percent of total uranium in the sample contained within the size fraction.

The term "location category" (column 3 in the table) denotes the following:

Location category	
I	Surface sample, near side wall
II	Surface sample, in impact zone
III	Sample from 1 m depth, near side wall
IV	Sample from 1 m depth, in impact zone

Figures C-1 to C-4 illustrate the size and DU distributions and DU concentrations in the samples grouped, as indicated, by location category. The size categories are themselves grouped into the four shown, combining several of the size fractions listed in Table C-1. The first bar signifies the mass percent of the size fraction, the central bar indicates the DU concentration in mass percent, and the third bar signifies the mass percent of DU of the total sample contained in that fraction.

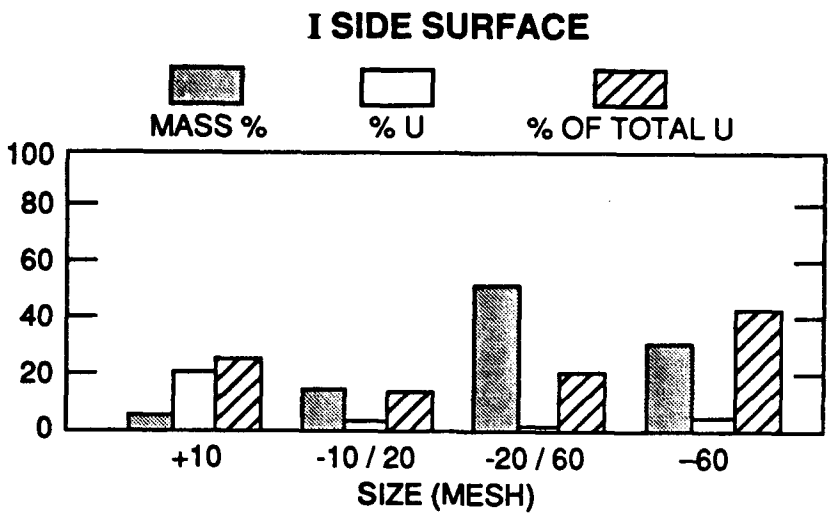

FIGURE C-1. Sand and DU Distribution in Location I Samples.

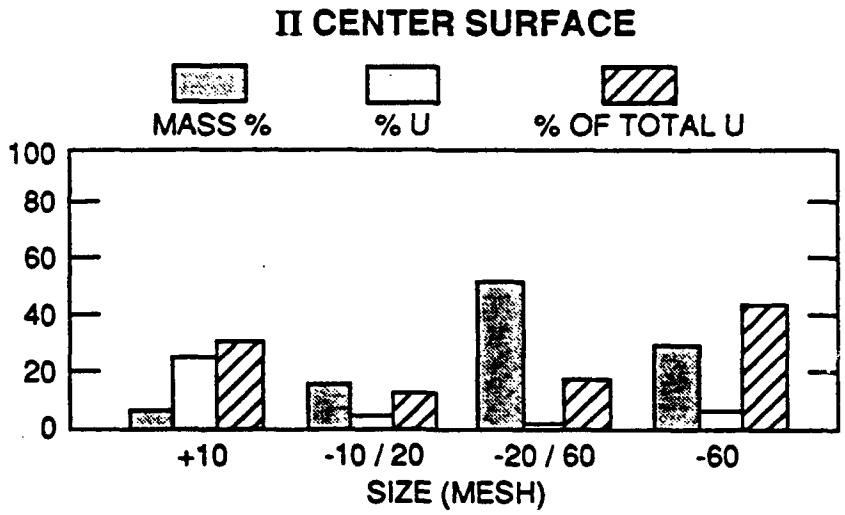

FIGURE C-2. Sand and DU Distributions in Location II Samples.

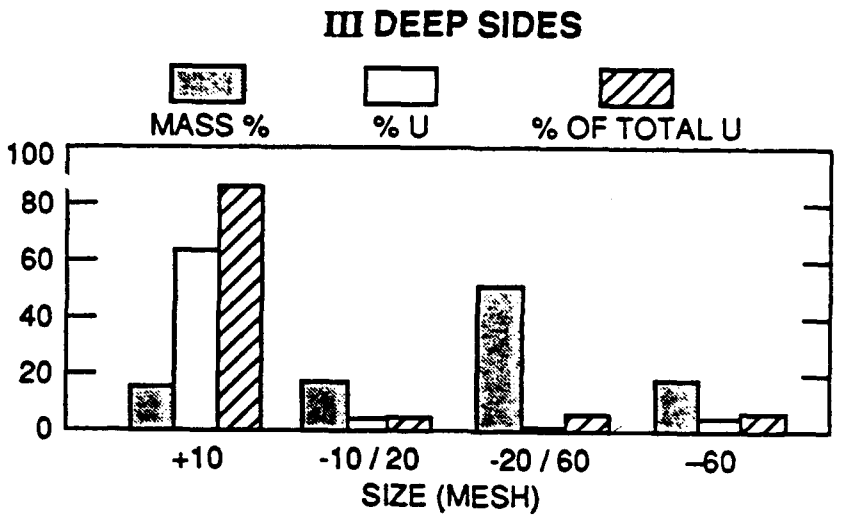

FIGURE C-3. Sand and DU Concentrations in Location III Samples.

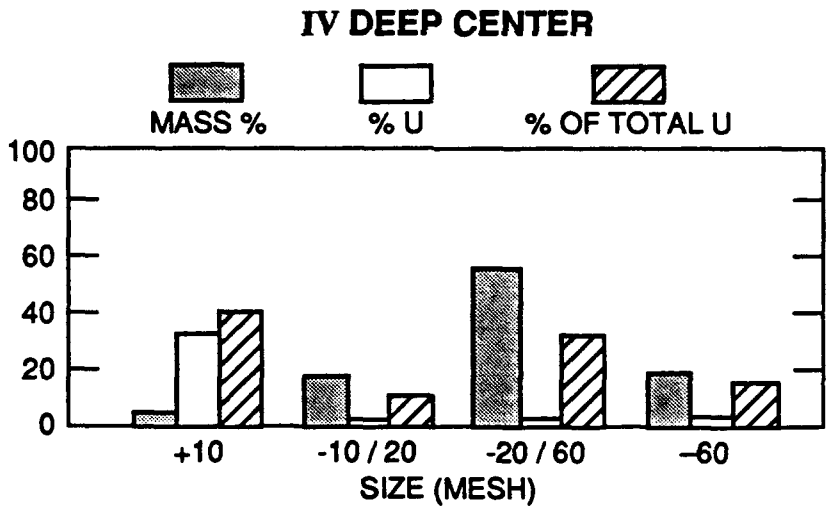

FIGURE C-4. Sand and DU Distributions in Location IV Samples.

TABLE C-1. SIZE AND URANIUM DISTRIBUTIONS IN SAND SAMPLES FROM THE BUTT

Sample No.	Location	Location category		Mesh size +10	(10 X 16)	(16 X 20)	(20 X 30)	(30 X 40)	(40 X 60)	(60 X 80)	(80 X 200)	-200	U conc. in total sample (%)
1	3-3-0	I	Mass (%)	4.00	7.10	11.3	21.7	17.7	18.7	6.10	7.20	6.20	
			U conc. (%)	7.37	3.70	2.70	2.10	2.20	1.70	1.60	6.50	17.40	3.76
			U (%)	8.03	7.16	8.31	12.42	10.61	8.66	2.66	12.75	29.40	
2	6-3-0	I	Mass (%)	2.50	5.80	10.2	20.	17.6	18.5	6.40	9.30	9.80	
			U conc. (%)	5.35	1.61	1.04	0.70	0.85	0.83	2.03	2.87	4.80	1.64
			U (%)	8.14	5.70	6.46	8.50	9.11	9.34	7.92	16.23	28.61	
3	9-3-0	II	Mass (%)	9.77	4.87	8.40	17.03	14.97	18.01	6.30	10.10	10.55	
			U conc. (%)	19.91	4.13	2.60	1.49	1.02	1.21	1.79	2.975	42.18	8.32
			U (%)	24.83	2.57	2.79	3.13	1.96	2.79	1.44	3.68	56.82	
4	12-1-0	II	Mass (%)	2.40	4.40	6.60	14.1	16.6	18.1	7.60	12.00	18.3	
			U conc. (%)	56.20	12.00	3.10	1.40	4.20	1.50	10.80	1.30	4.60	5.07
			U (%)	26.62	10.42	4.04	3.90	13.76	5.36	16.20	3.08	16.62	
5	12-3-0	II	Mass (%)	2.10	5.00	8.50	15.4	14.8	15.2	6.10	11.2	21.7	
			U conc. (%)	29.30	4.00	1.60	1.00	1.10	1.30	2.10	3.10	2.90	2.57
			U (%)	23.94	7.78	5.29	5.99	6.63	7.69	4.98	13.51	24.48	
6	15-6-0	I	Mass (%)	3.90	5.50	7.80	14.9	12.5	14.2	6.00	11.7	23.60	
			U conc. (%)	16.10	5.70	3.64	2.68	1.36	1.88	3.60	5.41	9.31	5.11
			U (%)	12.29	6.14	5.56	7.81	3.33	5.22	4.23	12.39	43.03	
7	3-6-0	I	Mass (%)	1.50	3.80	6.80	15.2	13.3	20.2	7.00	11.4	20.8	
			U conc. (%)	14.71	6.59	3.12	3.10	0.52	0.64	0.84	1.81	3.95	2.44
			U (%)	9.05	10.27	8.69	19.33	2.84	5.27	2.44	8.44	33.71	
8	6-6-0	I	Mass (%)	8.70	5.70	8.80	17.0	15.1	17.6	6.50	9.00	11.6	
			U conc. (%)	34.35	5.58	1.54	1.54	0.56	0.82	1.37	2.28	4.06	5.05
			U (%)	59.14	6.29	2.68	5.19	2.46	4.76	2.93	7.23	9.32	
9	9-6-0	II	Mass (%)	6.10	5.90	9.10	18.4	16.6	20.3	7.00	8.20	8.50	
			U conc. (%)	38.18	3.88	2.01	0.86	0.45	0.98	1.26	2.54	4.71	3.87
			U (%)	60.17	5.91	4.73	4.11	1.92	5.15	2.28	5.38	10.35	
10	12-6-0	II	Mass (%)	5.40	6.80	10.3	20.0	18.5	18.6	6.20	6.80	7.40	
			U conc. (%)	3.04	3.27	1.72	1.24	0.89	1.12	1.34	0.29	5.04	1.67
			U (%)	9.81	13.30	10.58	14.86	12.33	14.90	1.07	20.48	22.29	
11	6-6-3	III	Mass (%)	3.60	7.30	11.5	22.6	19.9	18.8	6.00	6.00	4.40	
			U conc. (%)	15.78	5.76	1.93	1.26	1.10	1.25	2.09	3.42	6.21	2.55
			U (%)	22.24	16.45	8.71	11.19	9.72	15.41	8.03	14.60	10.71	
12	12-6-3	IV	Mass (%)	4.10	7.50	11.0	20.0	18.4	18.7	6.00	6.60	7.60	
			U conc. (%)	71.30	3.93	1.50	1.26	1.00	14.10	1.56	2.19	4.97	7.07
			U (%)	41.33	4.17	2.33	3.57	2.60	37.20	1.33	2.04	5.34	
13	15-6-3	III	Mass (%)	2.80	7.40	11.0	21.2	18.2	19.2	6.20	6.50	7.50	
			U conc. (%)	19.16	3.99	1.14	0.98	0.71	0.36	1.62	2.71	4.85	2.00
			U (%)	26.78	14.75	6.25	10.37	6.48	3.40	5.03	8.79	18.14	
14	18-6-3	III	Mass (%)	26.78	4.95	7.04	13.36	11.43	12.47	4.09	4.25	4.83	
			U conc. (%)	37.58	3.06	2.12	1.39	1.04	1.21	2.22	3.67	5.49	35.40
			U (%)	90.81	0.43	0.42	0.52	0.34	0.43	0.26	0.44	0.75	

TABLE C-1 (CONCLUDED)

Sample No.	Location	Location category		Mesh size +10	(10 X 16)	(16 X 20)	(20 X 30)	(30 X 40)	(40 X 60)	(60 X 80)	(80 X 200)	-200	U conc. in sample (%)
15	15-6-3	III	Mass (%)	4.70	7.20	11.0	21.1	17.6	18.8	6.00	6.00	7.60	
			U conc. (%)	21.90	2.76	1.69	1.09	0.71	0.72	1.35	2.70	5.04	
			U (%)	40.69	7.89	7.36	9.06	4.93	5.33	3.21	6.41	15.15	
16	6-6-3	III	Mass (%)	3.11	7.40	10.6	20.7	17.8	18.9	6.30	6.50	8.80	
			U conc. (%)										
			U (%)										
17	9-6-3	IV	Mass (%)	8.70	7.20	10.6	20.2	16.8	17.4	5.70	6.30	7.20	
			U conc. (%)	19.17	4.03	1.76	1.16	0.98	1.00	1.80	2.85	5.18	3.37
			U (%)	49.46	8.61	5.54	6.93	4.88	5.18	3.04	5.32	11.06	
18	12-6-3	IV	Mass (%)	9.60	6.70	10.0	19.6	18.0	17.7	5.70	6.30	6.40	
			U conc. (%)										
			U (%)										
19	15-6-3	III	Mass (%)	4.20	6.80	10.5	19.9	18.4	19.3	6.20	6.60	8.00	
			U conc. (%)										
			U (%)										
20	18-6-3	III	Mass (%)	16.2	7.10	10.10	18.6	15.0	16.0	5.10	5.50	6.50	
			U conc. (%)	24.11	5.57	1.30	1.21	1.01	1.60	1.00	3.60	5.74	5.69
			U (%)	68.66	6.96	2.31	3.95	2.67	4.51	0.90	3.48	6.56	